University of Southern Queensland

Faculty of Health, Engineering and Sciences

Fabric Filter Shaker Drive Crank Assembly Operation Analysis

A dissertation submitted by

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towards the degree of

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ENG4111/4112 Dissertation Project

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CERTIFICATION

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

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[redacted]

Signature

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Date

ABSTRACT

Mt Piper Power Station (MPPS) is a 1,400 MW power station located two hours west of Sydney near the NSW country town Lithgow. Since the commencement of operations in 1993 there have been ongoing failures in the fabric filter infrastructure, which has impacted the environmental efficiency of the fabric filter, increased maintenance requirements and subsequent operating costs. A review of the performance of the Howden fabric filter infrastructure located at MPPS, and subsequent application of findings to industry wide fabric filter infrastructure, is the focus of this dissertation.

Efficiency of dust removal, as described by Wang et al (2004), is the key consideration in fabric filter design and specifically the shaker drive crank assembly (SDCA), the major fabric filter component responsible for delivering forces to the filtration infrastructure. A series of studies undertaken by Dennis (1975) describe the correlation between the primary loading inputs, including; quantity of shakes per cycle, shaking frequency, shaking amplitude and fabric filter bag acceleration. Understanding the impact of these variables is critical to analysing the existing design and the development of any design recommendations.

To gain an understanding of the SDCA failures, an analysis of the proprietary design and associated design iterations was undertaken. This involved reviewing the fabrication and quality assurance process, the current maintenance regime and inspection of failed SDCA components. The various designs were then modelled with simulated loading applied. Following this assessment, a root cause of the failures along with contributing factors were identified and used as the basis for proposing design modifications and refinement to the fabrication and quality assurance process.

Through modelling and stress simulation of the proprietary design and various iterations of this design, the stress raisers apparent in the design have been verified. This has provided the basis for developing a modified design which minimises the impact of the stress raiser.

Through the application of modern modelling techniques to the SDCA, a potentially more cost effective design can be developed. Further, there is the opportunity to modify the quality assurance process associated with the SDCA fabrication to support the continued development of the design.

ACKNOWLEDGEMENTS

Undertaking this project would have been significantly more difficult without the guidance of my supervisors, Ray Malpress and Andreas Helwig along with the support and encouragement from my partner Brooke.

In addition, I would also like to thank my work colleagues at Mt Piper Power Station for their assistance throughout.

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NOMENCLATURE

Δ	=	Delta (Range)
π	=	Pi (3.14159)
$\bar{a}$	=	Average acceleration
cps	=	Cycles per second
d	=	Diameter
f	=	Frequency
g	=	Gravitational acceleration $(32.2\, ft/s^2\ or\ 9.81\, m/s^2)$
K	=	Fabric Resistance
kg	=	Kilogram
kW	=	Kilowatt
L	=	Length
m	=	Metre
mm	=	Millimetre
N	=	Newton
N.m	=	Newton Metre
n	=	Number

OD = Outside Diameter

rpm = Revolutions per minute

rps = Revolutions per second

ρ = Density

P = Power

p = Pressure

s = Second

T = Torque

t_{clean} = Duration of each cell cleaning cycle

t_s = Interval between cell cleaning cycles

µm = Micrometre

UDL = Uniformly Distributed Load

v = Velocity

V = Volt

W = Watt

$\bar{Y}$ = Average amplitude

GLOSSARY

BHT	=	Brinnell Hardness Test
BPS	=	Bayswater Power Station
DP	=	Differential Pressure
EA	=	Energy Australia
EPA	=	Environmental Protection Agency
FEA	=	Finite Element Analysis
FEM	=	Finite Element Method
GOC	=	Government Owned Corporation
JHA	=	James Howden Australia Pty Ltd
MPPS	=	Mt Piper Power Station
NDT	=	Non Destructive Testing
NEM	=	National Electricity Market
O&M	=	Operations and Maintenance
OEM	=	Original Equipment Manufacturer
PM	=	Particulate Matter
POEO	=	Protection of Environmental Operations

PTFE	=	Polytetrafluorethylene
PV	=	Photo Voltaic
QA	=	Quality Assurance
SDA	=	Shaker Drive Assembly
SDCA	=	Shaker Drive Crank Assembly
SHS	=	Square Hollow Section
US	=	United States

CHAPTER 1: INTRODUCTION

1.1.BACKGROUND

Mt Piper Power Station (MPPS) is a 1,400 MW power station located two hours west of Sydney near the NSW country town Lithgow. The power station comprises of two 700 MW units, with the units first commissioned in 1992 and 1993. Until 2013, the power station was owned and operated by government owned corporation (GOC) Delta Electricity, when MPPS and the nearby Wallerawang Power Stations were acquired by Energy Australia (EA).

In November 2014, EA announced that it would permanently close Wallerawang due to ongoing reduced energy demand, lack of access to competitively priced coal and high operating costs (Energy Australia, 2017), which primarily related to the age and environmental efficiency of the plant. However, MPPS remains critical to the base load power generation in NSW, as the 4th largest coal fired power generator, behind the Hunter Valley based Bayswater Power Station (BPS), Liddell Power Station and Eraring Power Stations.

Critical to the environmental performance of a coal fired power station is the ash filtration process, which at MPPS is managed utilising a fabric filter for each of the two units. The fabric filter traps particulate matter (PM) contained in the flue gas prior to the emission from the stack. The pollutants captured by the fabric filter include fly ash, mercury, lead and cadmium among others (Staudt, 2011).

Since the commencement of operations at MPPS in 1994, there have been ongoing failures in the fabric filter infrastructure, which has impacted the environmental efficiency of the fabric filter, increased maintenance requirements and subsequent operating costs.

A review of the operational performance of the Howden fabric filter infrastructure located at MPPS, and subsequent application of findings to industry wide fabric filter infrastructure, is the focus of this paper.

1.1.1 Current State of the Coal Fired Power Generation Industry

Australia continues to be heavily reliant on the use of coal fired power generation, with over 70% of the electricity generated in 2014 from either a black or brown coal source (Australian Energy Regulator, 2014), with Australia's eastern states the most reliant on coal, as noted in Figure 1-1, detailing Australia's electricity consumption by region in 2014.

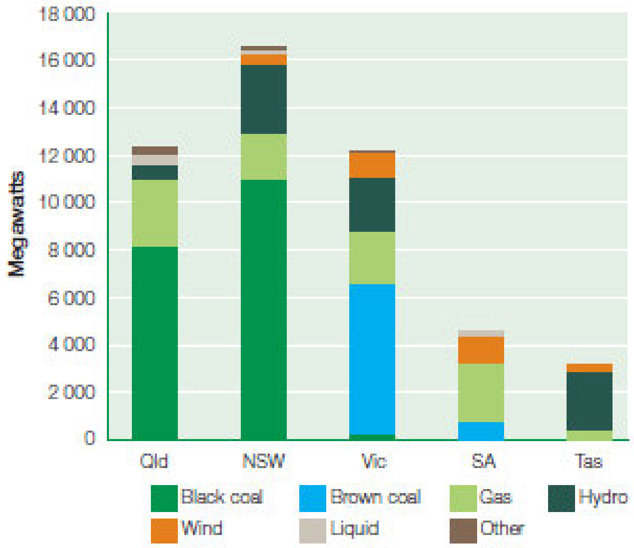

Figure 1-1: Electricity Consumption by Region (State of the Energy Market, 2014)

The use of coal fired power in Australia has been declining over the past decade with the introduction of new gas and renewable power generation sources. As noted in Figure 1-2, since 2007 / 2008 there has been a decline in the increase of coal fired power generation, with a decrease in usage experienced since 2012 / 2013.

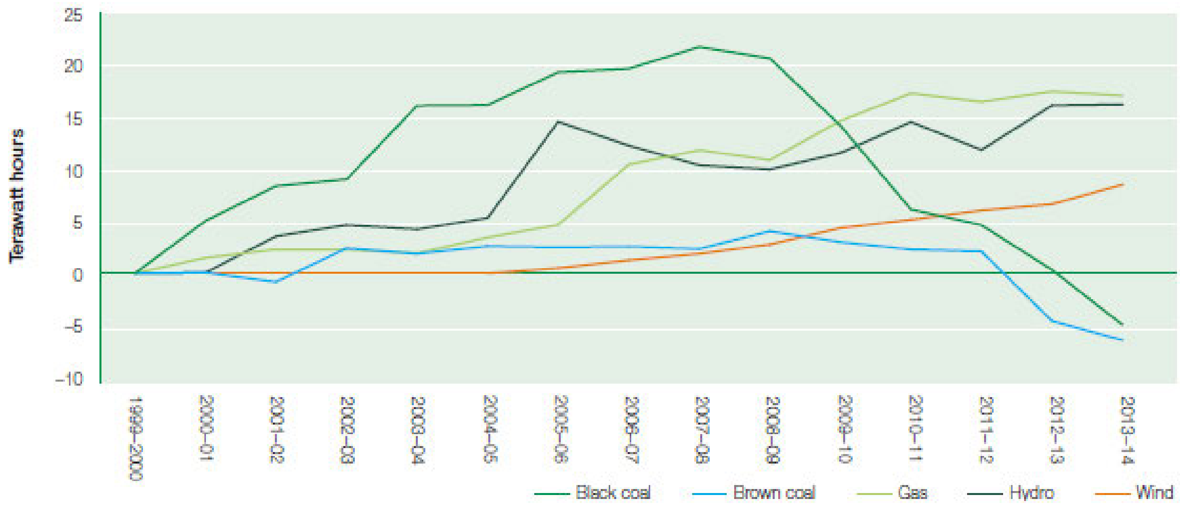

Figure 1-2: Annual Decline of Coal Fired Generation (State of the Energy Market, 2014)

This reduction in coal fired generation usage has occurred in conjunction with an increase in the electricity consumed from alternative energy sources such as the use of solar PV, wind, gas and hydro. Much of this has been driven by climate change policies implemented over the past decade, including; the expansion of the Renewable Energy Target scheme in 2007, contributing another 2,300MW of wind capacity to the grid during the following 6 years, increases in carbon pricing associated with the carbon tax increasing the operating cost of coal fired plant (State of the Energy Market, 2014), in conjunction with household incentives to utilise renewable energy through the use of Small Generation Units (Your Energy Savings, 2017).

Figure 1-3 detailing the power generation assets in Australia's eastern states as of 2014, demonstrates that whilst there are many alternative electricity supply sources, there is still a significant amount of development required to replace the base load generated by the coal fired sites around South East QLD, Sydney and Melbourne.

Figure 1-3: Power Generation Assets in Australia’s Eastern States (State of the Energy Market, 2014)

Australia’s coal fired generators, such as AGL, are continuing to forecast in excess of 30 years of asset life for some of Australia’s largest coal fired power plants (Hannah, 2015), which based on Figure 1-3 appears a viable projection. Therefore, maximising the efficiency of existing plant and minimising operational expenditure is critical for coal fired power plants to remain viable whilst this transition away from coal fired power continues.

The operations undertaken by coal fired generators in NSW is governed by the Protection of Environmental Operations (POEO) Act 1997 (About the POEO Act, 2017), therefore activities such fly ash filtration are to be administered in accordance with the requirements identified within the act.

To summarise, the business pressures within the coal fired power generation industry driving the Fabric Filter Shaker Drive Crank Assembly (SDCA) Operational Analysis are as follows:

1. Historical SDCA Failures – A history of fabric filter SDCA failures since MPPS commenced operations, without identification of a solution to rectify the problem
2. Environmental Performance – Responsibility to operate in accordance with the POEO Act 1997
3. Financial Performance – Growing pressure on financial efficiency within the power generation industry with an increasing number of competitors and methods for power generation
4. New Ownership – Recent purchase of MPPS by private enterprise EA from GOC Delta Electricity

1.1.2 Coal Fired Power Station Operation

The fabric filter is an integral part of the overall coal fired power generation operation, managing the fly ash emission generated from the coal combustion process. The schematic in Figure 1-4 and associated steps detail the coal fired power station operation and relevance of post combustion filtration.

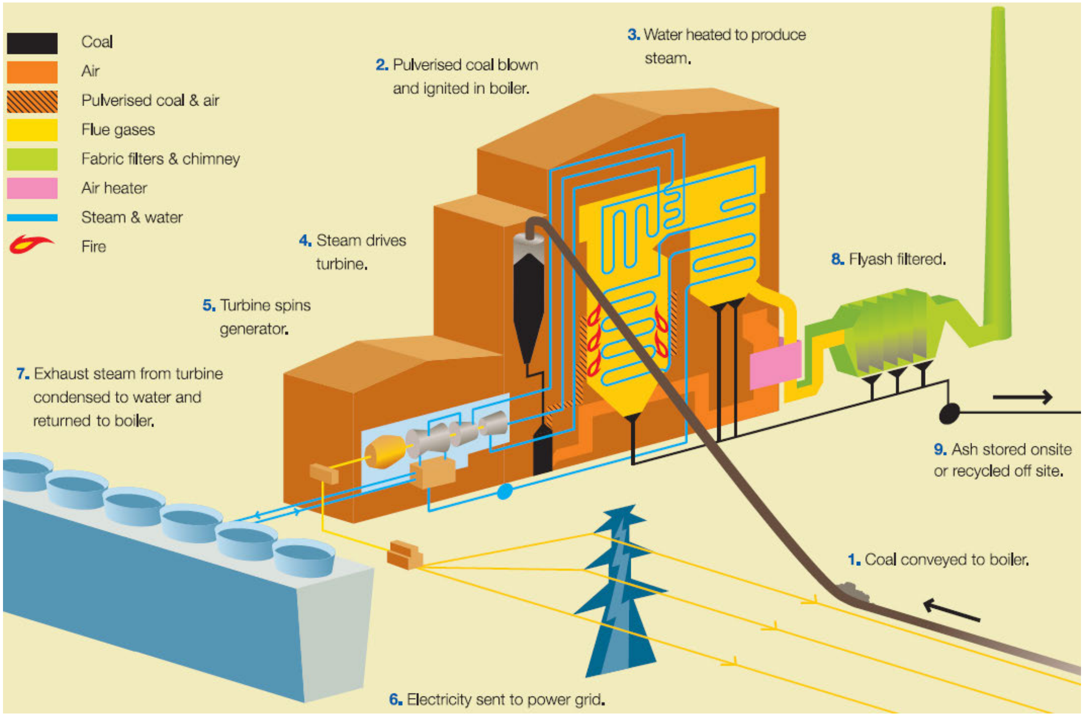

Figure 1-4: The Electricity Generation Process (CS Energy, 2017)

The typical coal fired power generation process is described in the following steps, with reference to the *CS Energy Technical Information for Electricity Generation* at Callide Power Station (CS Energy, 2017):

1. Coal is delivered to the power station from stockpiles by conveyor.

2. Coal is ground to a fine dust in pulveriser mills, then mixed with hot air and blown to the burners of the boiler.

3. The coal enters the boiler, a large vessel with walls containing steel tubes filled with water pumped at high pressure, and is ignited. The heat from the boiler, heats the

water in the tubes, converting the water to steam as it rises from the base to the top of the boiler.

4. The steam is then piped to the turbine, which when impacted by the high pressure steam, rotates the turbine blades.

5. This rotation of the turbine blades, which are attached to the turbine shaft, produces electricity via an electromagnet in the attached generator windings.

6. Electricity is transported to consumers via transmission lines.

7. Steam from the turbine is condensed to water when interacting with water from the cooling tower, the water is then recycled and returned to the boiler.

8. The coal combustion produces both bottom ash and flue gas containing fly ash:

    a. The bottom ash drops to the base of the boiler where it is then transported to a silo by a submerged chain conveyor.

    b. The flue gas containing fly ash is drawn through the ash filtration process by induced draft fans, with filtration by either fabric filters or electrostatic precipitator. The remaining flue gas is then emitted via the stack into the environment. The filtered fly ash is captured in hoppers at the base of the fabric filter / precipitator.

9. The bottom ash is transported by trucks to the ash repository. The fly ash is either transported to the ash repository either by truck or pipe, or sold to the cement manufacturing industry.

1.1.3 Fly Ash Filtration Process

Within the coal fired power generation industry, there are two primary filtration methods used for capturing the fly ash generated by coal combustion, they are the use of electrostatic precipitators or the use of a fabric filter.

Fabric Filters are commonly used throughout the coal fired power industry in Australia, with most of the larger power generation sites throughout QLD and NSW, including MPPS, BPS, Liddell, Eraring and Gladstone among others, utilising fabric filter technology.

Figure 1-5 demonstrates the process flow specific to the ash capture process. Coal enters the boiler where it is ignited and transferred to heat, with by-products of bottom ash, economiser grits or fly ash. The bottom ash and economiser grits are typically deposited by truck in an ash repository.

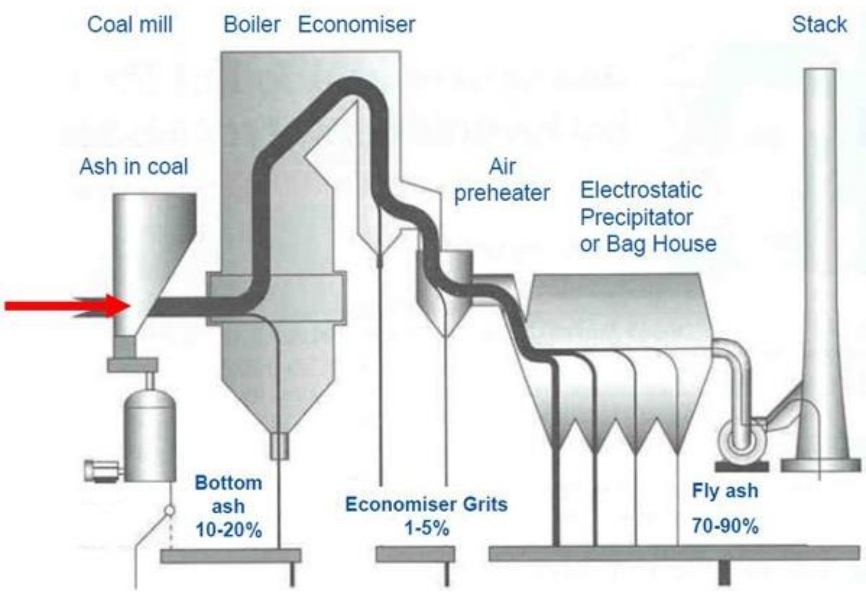

Figure 1-5: Ash Capture Process (Fly Ash Australia, 2010)

The fly ash is drawn through the filtration process by the use of Induced Draft (ID) fans, where it passes through the filter medium, whether it be precipitators or fabric filter bags.

As shown in the above schematic, between 70 and 90% of the coal by-product is removed during this process.

In the case of the fabric filter bag house, once captured on the fabric filter bags, the periodic shaking motion of the SDCA releases the ash from the fabric filter bags, where it falls into hoppers at the base of the fabric filter. Once in the hoppers, it is transported to a silo by conveyor or pipe line, where a portion is typically used by other manufacturers for cement making, with all residual fly ash transported by pipe or truck to the ash repository.

A feature of the fabric filter process highlighted in the above image and by Felix (1986) is the location of the filter cells with respect to the gas flow, with those located on the boiler side collecting a greater amount of PM more frequently, with the density of dust in the flue gas reducing as it moves from the boiler side to the stack side. This potentially varies the operating parameters throughout the fabric filter, with cells on the boiler side experiencing a greater frequency of use.

1.1.4 Shaker Drive Crank Assembly (SDCA) Introduction

The SDCA is the component within the fabric filter responsible for dislodging the dust captured on the fabric filter bags by applying an oscillating (or shaking) motion to the bags, via the attached shaking rack, allowing the dust to gravity feed to the hoppers at the base of the fabric filter.

The following Figure 1-6 shows the SDCA side view, front view and as part of the shaker mechanism assembly.

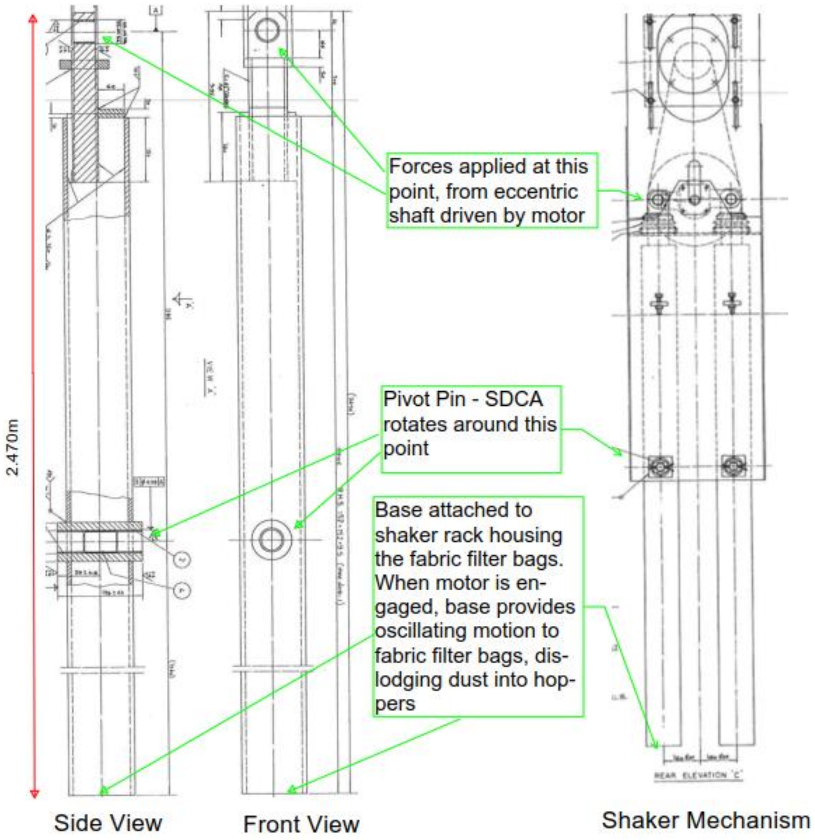

Figure 1-6: SDCA Side View, Front View and Shaker Mechanism

As a means of introduction, the SDCA is driven by a motor and eccentric shaft at the top, it then rotates about a central pivot point, which in turn provides an oscillating force to the base. The base of the SDCA is connected to the shaker rack which supports the fabric filter bags. This oscillating motion is transferred to the fabric filter bags, dislodging the captured dust.

The SDCA motor is engaged for short cycles periodically, typically once a nominated volume of dust has been captured on the fabric filter bags. Chapter 2 provides a detailed overview of the SDCA operational process.

1.1.5 Wider Industry Relevance

Outside of the coal fired power generation industry, fabric filter manufacturer Howden (2017), supply fabric filter infrastructure for use in various other applications, including:

- Cement / Lime
- Iron / Steel
- Mining (Aluminium, Copper, Zinc, Lead and Nickel)

The objective of this analysis, is to identify a solution that is relevant to MPPS, which can be utilised at other power stations and transferred to these other industries.

1.2.PROJECT AIM

The aim of this project is to conduct an engineering review of the fabric filter shaker frame infrastructure at MPPS and ascertain if there is a design modification which can be implemented, at MPPS and throughout industry. Any identified solution needs to maintain the operational capabilities of the shaker frame, whilst increasing longevity of the plant and subsequently reducing the financial impact associated with ongoing maintenance.

1.3.PROJECT OBJECTIVES

To achieve the project aim, six project objectives have been identified to provide the basis for understanding the potential design problem, identifying the contributing factors, then determining if a suitable design alternative is available.

Following is a summary of the project objectives and their associated relevance to the outcome of this dissertation:

1 **Research the functionality of the fabric filter** within industry and the purpose for its use in industrial facilities, providing context to the project aim and subsequent project objectives.

2 **Identify the design variables impacting fabric filter operation.** These variables shall be used as the limitations for determining the suitability of any proposed design modifications.

3 **Investigate historical fabric filter performance specific to the MPPS**, including the proprietary SDCA design and any previous design modifications. Understanding the historical performance of the plant will assist in determining the failure causes and their associated operational / financial impact.

4 **Understand the failure modes** that have historically impacted the fabric filter infrastructure, then determine any root cause/s and any contributing factors associated with these failures. Determining the root cause/s and contributing factors, will provide the basis for any alternative design concepts as they will likely be focussed on mitigating these factors.

5 **Propose appropriate design / process modifications** based on previous failure modes and prove / disprove if they would be suitable alternatives to the existing design, utilising calculations and modelling software where required. This analysis will verify if a suitable solution is available that meets operational requirements.

6 **Establish a suitable methodology for implementing design / process modifications and undertake the associated cost assessment** to determine the financial viability and overall feasibility of modifying the design. Should a suitable alternative not be identified,

provide an assessment as to why the existing design is the most appropriate, along with any recommendations as to how the design life can be maximised.

1.4. DISSERTATION OVERVIEW

The following chapters of the dissertation will address the project objectives as follows:

- Chapters 2.1 and 2.2: Objectives 1 and 2 above will be addressed, with a literature review of the functionality of the fabric filter, previous fabric filter research and analysis of the design variables
- Chapter 2.3: Objective 3 is described based on inspections of the MPPS site, discussions with operational personnel and a review of the Original Equipment Manufacturer (OEM) design information
- Chapters 3.1, 3.2 and 3.3: Chapter 3.1 provides a background into Objective 4, understanding the failure modes, with chapters 3.2. and 3.3 detailing the Operations and Maintenance (O&M) processes in place
- Chapter 3.4: Objective 5 is discussed, with an overview of proposed solutions to the issues identified in chapters 3.1 to 3.3
- Chapter 4: Objectives 4, 5 and 6 are addressed with theoretical analysis and computational assessment of existing and proposed solutions
- Chapter 5: Objectives 5 and 6 are addressed through the discussion of results obtained from Chapter 4, identifying potential changes to the existing design / process, then ascertaining the feasibility of any proposed changes

- Chapter 6: A summary of the results is provided with reference to all the project objectives, in addition to an overview of the project contribution with reference to AQF level 8 criteria

CHAPTER 2: BACKGROUND AND LITERATURE REVIEW

The intent of this section is to identify the purpose and functionality of the fabric filter within industry, and establish the design variables that impact fabric filter operation in general, as well as the fabric filter infrastructure specific to MPPS. Additionally, an assessment of previously recorded literature specific to the objectives of this paper will be undertaken and reported as required.

This research is intended to provide the background to any design constraints that should be considered, in conjunction with historical operational data obtained from MPPS, when the proposal and assessment of solutions to the SDCA operational analysis are undertaken.

2.1 FABRIC FILTER HISTORY

The use of textile fabrics for the separation of airborne dust and fume is included in much of the recorded history of man, potentially dating back to circa 5000 BC, where millers and bakers used cloth over their mouths to prevent inhalation.

In the 19th and 20th centuries, fabric filtration emerged throughout industry to protect workers from dust and other airborne infectious agents, along with the respiratory protection used by fire fighters in industrial / military environments containing chemical, biological and radiological aerosols. During this period, industry also adopted the use of fabric filtration for the recovery of valuable products contained in dusts and fumes in non-ferrous and refining operations, where it was viewed that escaping fumes equated to an economic loss. This coincided with manufacturers' commencing the development of large volume fabric filters that offered both the capacity to recover product from gases, but also support worker health and nuisance control.

The movement to utilizing filtration that focused on minimizing impact on the local population and environment gained momentum with damage suits and economic penalties associated with some arsenic and lead facilities where fumes were proven to have impacted the surrounding area. (Billings, 1970)

Today, the use of fabric filtration in the power generation industry is primarily focused on minimizing the impact on the local environment, with all dust captured being stored in an ash dam typically located adjacent to the power station, similar to Figure 2-1 below.

Figure 2-1: Mt Piper / Wallerawang Ash Dam (Lithgow Environment, 2017)

However, over recent decades, the fly ash for many coal fired power stations has become a saleable product. At MPPS since opening in 1994, over 2 million tonnes of fly ash has been used for fly ash based products, such as a supplementary cementitious material (Fly Ash Australia, 2017).

The fabric filter provides coal fired power stations the capability to utilize some of the fly ash, subsequently minimizing the footprint of ash dam storage required, as well as providing a potential economic benefit through the sale to cement manufacturers.

2.2 FABRIC FILTER DESIGN

As described by Wang et al (2004) the theory of fabric filter design states that at low velocities, the gas flow through a fabric filter is viscous, and the pressure drop across the filter is directly proportional to flow:

$$\Delta p = Kv$$

Where Δp is the pressure, K is the fabric resistance and v is the gas velocity.

This is relevant to all three variants of fabric filter design, where the principle of particles contained within a gas captured by fibres is essentially the same. The variations in the fabric filter designs are related to the cleaning mechanism responsible for dislodging the dust from the fabric, which are described with reference to James Turner et al (1998) and Charles Billings et al (1970) below:

- **Pulse Jet Cleaning:** Compressed air provides a surge of air through the filter bag, causing it to expand rapidly through a combination of fabric deformation and flow reversal, forcing the dust particles to become dislodged once the bag reaches its extension limit. The advantage of this method is that it is much faster than other forms of filtration, providing minimal disruption of operation.
- **Reverse Flow Cleaning:** The use of reverse flow was initiated by the introduction of glass fibre fabrics requiring a gentler means of cleaning. A low pressure flow

reversal is provided to the filter bags, this gently collapses the filter bags towards their centerlines, causing the dust cake to dislodge.

- **Shaker Cleaning:** Separate to the pulse jet and reverse flow cleaning techniques, shaker cleaning is not primarily reliant on gas flow. Rather the dislodgement of dust from the filter bags is caused by an energy transfer provided by a motor driven crank assembly to the fabric filter bag racks, which creates a sine wave along the fabric.

In the case of each fabric filter design variant, a successful design of a fabric filter, is dependent on five main design variables:

- Filter bag material
- Fabric cleaning design
- Air to cloth ratio
- Baghouse configuration, and
- Materials of construction.

For the purpose of this paper, I am concerned with design variables that will have a direct impact on the SDCA performance, therefore filter bag material is assumed to have a negligible impact as this is primarily a filtration efficiency consideration. Additionally, air to cloth ratio and baghouse configuration relate to the initial fabric filter design and associated plant installation which would likely incur a significant cost impact to modify retrospectively, therefore they are also beyond the scope of this paper

With reference to Wang et al (2004), following are the key considerations relating to design variables specific to the shaker cleaning fabric filter, which may be relevant to the SDCA operational analysis:

Materials of Construction: Carbon steel is typically used for fabric filter construction, with variations in steel grade subject to the required application.

Fabric Cleaning Design: Shaking combines normal and shear stresses impacting the dust-fabric interface; along with stresses developed by warping, binding and flexing of the fabric surfaces. Dust removal efficiency is a function of:

- Number of shakes per cycle
- Shaking frequency
- Shaking amplitude
- Bag movement acceleration

As an example of the above, Dennis (1975) detailed the results of a series of studies, described in *Fabric Filter Cleaning Studies*, which showed the relationship/s between the variants of shaker arm motion on the motion of shaker bags and the overall cleaning efficiency of the plant.

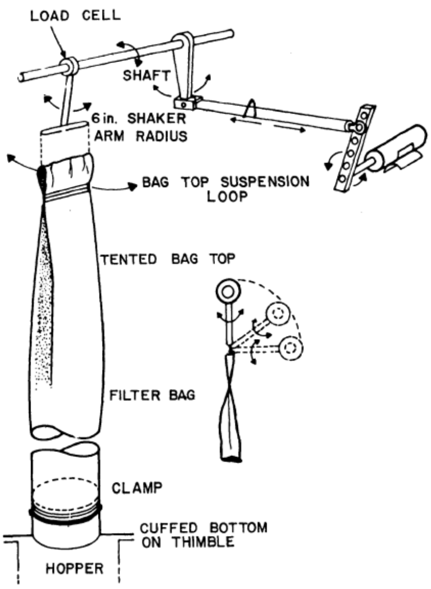

Figure 2-2: Apparatus used for modelling the variants of shaker arm and shaker bag motion (Dennis, 1975)

The approach used by Dennis for modelling the force and motion patterns of the shaker arms and filter bags involved constructing an apparatus, detailed in figure 2-2, which would simulate the fabric filter behavior under various conditions.

The following Figures 2-3 and 2-4 detail some of the variants modelled and the associated results. The below describes the effect of number of shakes, based on 8 cycles per second (cps), and the shaking amplitude on dust removal from 10 foot x 6 inch cotton bags (Dennis, 1975):

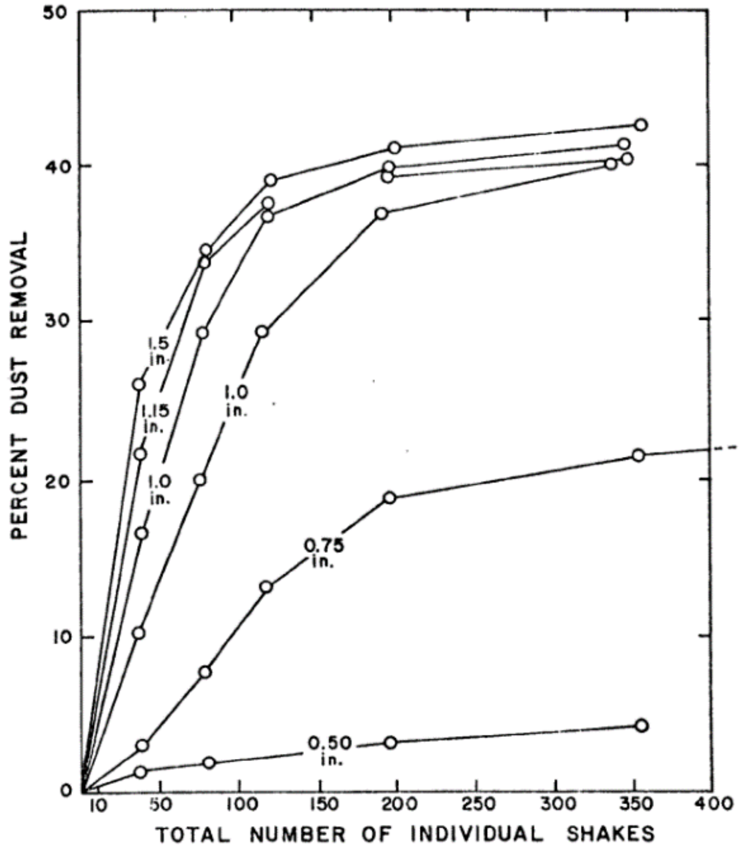

Figure 2-3: Filter Bag Shakes / Amplitude / Dust Removal at 8 cps (Dennis, 1975)

Figure 2-3 shows that for shaking peak to peak amplitude of 1 inch (25mm) or greater, that the greatest efficiency of dust removal per shake is achieved by 50 shakes. Once around 100 shakes is achieved, the efficiency reduces significantly.

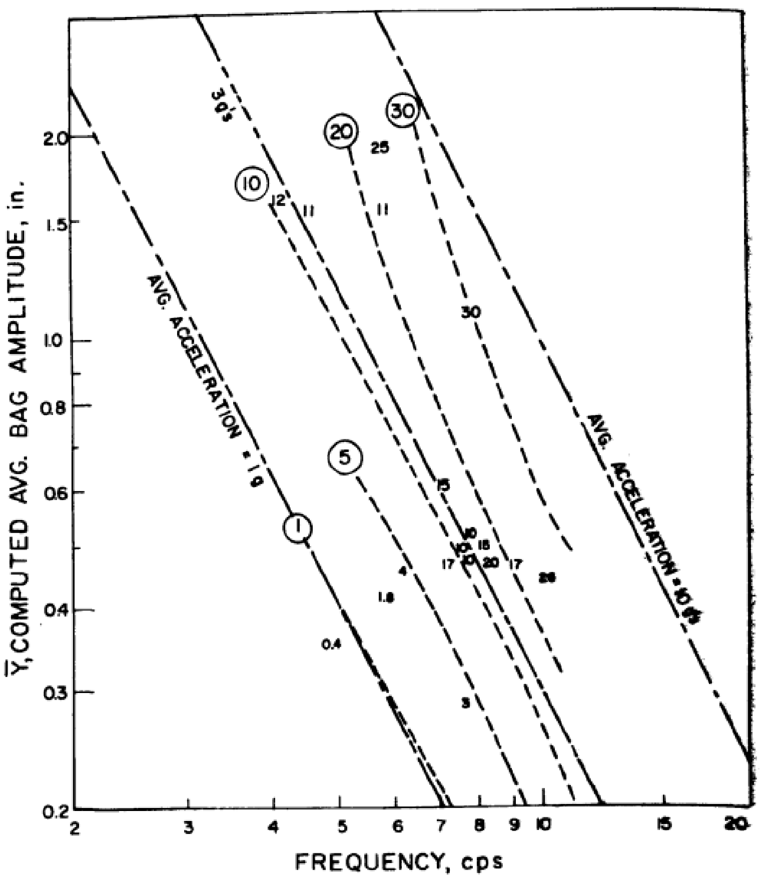

Figure 2-4: Dust removal / Acceleration / Amplitude / Frequency at 40 shakes (Dennis, 1975)

Figure 2-4 shows dust removal versus bag acceleration for 40 shakes. The broken line shows constant acceleration contour, whereas the dashed line and circled numbers show the constant dust removal contour. The uncircled numbers show actual dust removed at average bag amplitude coordinates. Review of this data identifies that dust removed is a function of amplitude, shaking frequency and acceleration, the empirical results derived in Fabric Filter Cleaning Studies (Dennis, 1975), explain this correlation with the following equation:

$$\bar{a} = 4\pi^2 f^2 \bar{Y}$$

This equation notes the average acceleration $\bar{a}$ is a function of frequency f and average amplitude $\bar{Y}$.

As noted above, these factors are critical to the performance of the fabric filter. Howden has specified operational parameters / materials relating to the above in their Fabric Filter O&M Manual (Howden, 1979), therefore part of the SDCA operational analysis will require the verification that these operational parameters / materials are being utilised. If not, an assessment as to the potential impact of any changes to these parameters will be required.

2.3 MT PIPER POWER STATION FABRIC FILTER

With reference to the Howden Fabric Filter O&M Manual (1979) in conjunction with information obtained from site inspections, this section provides an overview of the MPPS Fabric Filter plant, the key components impacting the performance of the SDCA, the prescribed operations and maintenance regime and performance history of the plant.

2.3.1 Mt Piper Fabric Filter Overview

The design of the MPPS Fabric Filter is shown in Figure 2-5, a photo of the framed picture provided with the original installation, taken from the maintenance compound adjacent to the Fabric Filter at MPPS.

The process for capturing ash on the filter bags as described in this image involves the ***poppet outlet dampers (1)*** and the ***poppet inlet dampers (4)*** opening, allowing ***clean gas (2)*** to exit the fabric filter, and ***dirty gas (3)*** to enter the filter. Once in the filter, the dirty gas passes into the cell through the ***fabric filter bags (6)***, which are supported by the ***base cell plates (5)*** and the ***shaker racks (8)***.

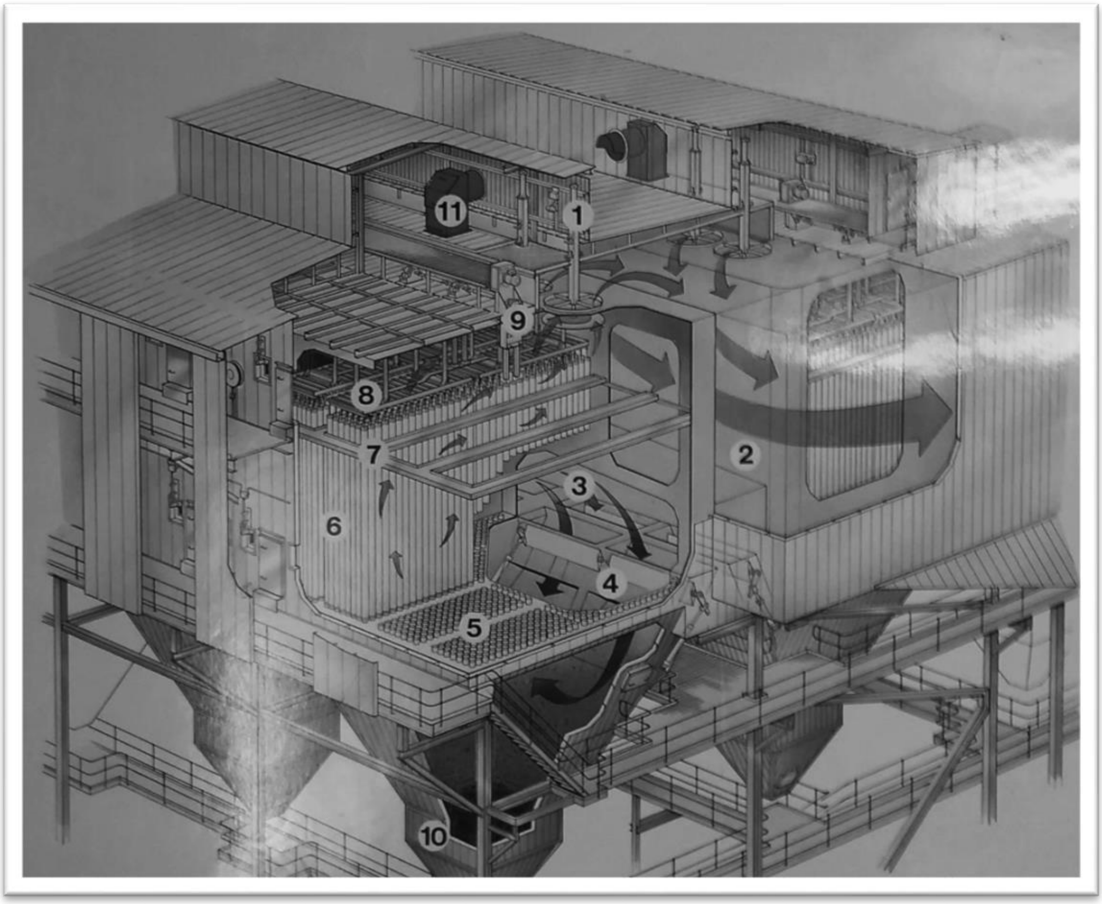

Figure 2-5: Howden Typical Shaker Type Fabric Filter Dust Collector

The process for removal of captured ash involves the ***poppet outlet dampers (1)*** and the ***poppet inlet dampers (4)*** closing, the ***cell ventilation (11)*** opening, the ***shaker drive (9)*** commencing operation engaging the SDCA, shaking the ***shaker racks (8)***, which in turn releases the ash from the fabric filters, which is gravity fed to the ***hoppers (10)***, from the hoppers the ash is released to either conveyor or pipeline by valve.

For maintenance access and operational inspection, ***walkways (7)*** are used to access locations at the top and bottom of the cells.

The operational performance of the ***shaker drive (9)*** and associated infrastructure is the focus of this dissertation.

2.3.2 Shaker Mechanism Componentry and Technical Data

The Howden O&M Manual (1979) details the SDCA componentry utilised and the design intent for its use. In providing a basis for the operational analysis of the SDCA, a comparison of the specified componentry and its intended use, against the current componentry and its actual use is required. Aside from providing context to the analysis, this is to ascertain if there are any operational modifications that have occurred since the plant was commissioned that may contribute to the performance of the SDCA.

A front view of the shaker mechanism for one cell is shown in Figure 2-6.

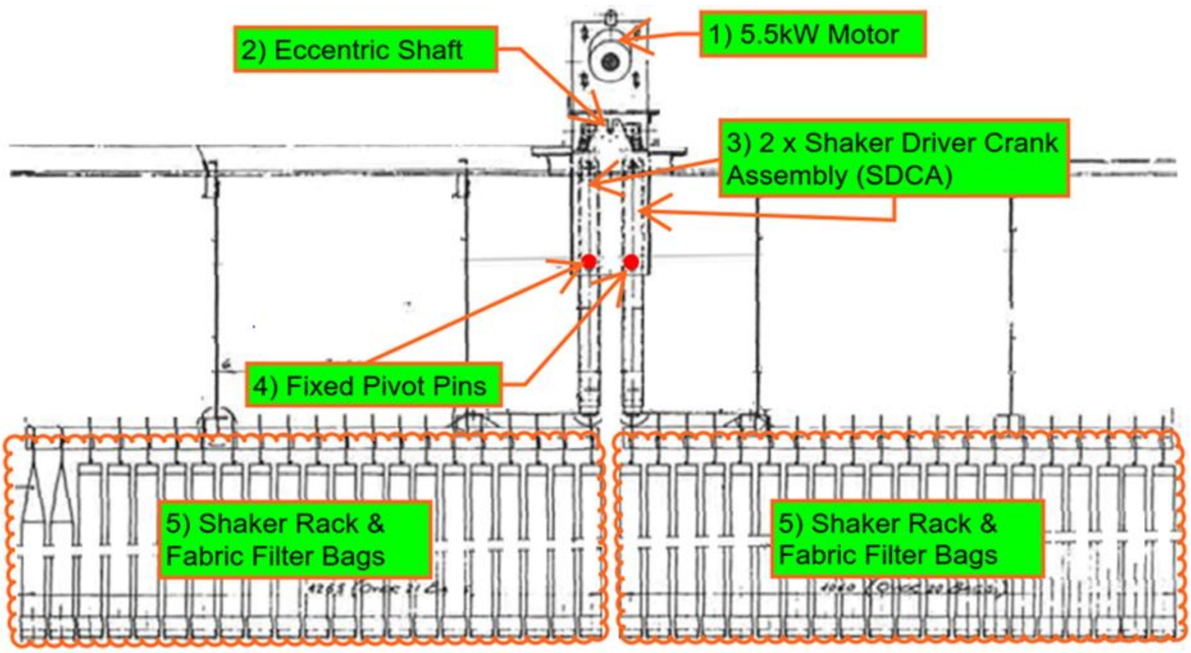

Figure 2-6: Shaker Mechanism – Front View (Howden, 1979)

Each cell contains 4 shaker mechanism assemblies, with a total of 40 cells per unit. As there are 2 units at MPPS, this equates to 80 cells in total.

A summary of the major components required within the shaker mechanism are listed below, with critical design values as per the listed requirements:

- 1 x Shaker Drive Assembly (SDA) – Including electric motor, v-belt drive, 2 x pulleys, bearings, drive shaft and shaker drive frame. The motor drives the motion of the SDCA:
    - Drive motor: Toshiba, 5.5kW, 415V, 6 pole, 960 rpm
    - Drive pulley size: 150mm OD
    - Driven pulley size: 500mm OD
    - Amplitude of shake: 3 settings – 20mm, 40mm or 60mm (Currently operating at 20mm)
    - Shaking Cycles Per Second: 6
- 2 x Shaker Drive Crank Assemblies (SDCA) – Including eccentric shaft, connecting rod, pivot pin and crank structure, they are rotated about the pivot pin by the SDA in +/- cycles, providing oscillation to the shaker racks via the connection straps attached to the base of the SDCA:
    - Shaker Drive Crank Assembly: Refer drawing 7001-0706 in Appendix D
    - Eccentric Shaft: Refer drawing 7001-0710 in Appendix D
    - Pivot Pin: Refer drawing 7001-0707 in Appendix D
- 2 x Connection Straps – Bolted to the base of each crank structure and shaker racks, they provide the motion to the racks to dislodge the dust:
    - Strap and Bolt Connection: Refer drawing 7001-0721 in Appendix D
- 2 x Shaker Racks – Bolted to the connection straps, the shaker racks secure the top end of the filter bags and provide the dynamic forces to the bags:
    - 160 bag rack (8 x 20 bags): 4060mm x 1565mm
    - 168 bag rack (8 x 21 bags): 4265mm x 1565mm

- 328 x Filter Bags – The top of the filter bags are secured to the shaker racks, with the base secured to the cell plates. With reference to the above image, there are 41 rows long x 8 rows deep of filter bags:
    - Cloth area per bag: 2.7965m^2
    - Diameter and length: 165mm x 5395mm
- 2 x cell plates – The cell plate forms the floor of the cell and contains spigots (cell rings) for securing the base of the 328 filter bags

To assist with modelling pertaining to the operation of the SDCA, the calculations in Table 2-1 estimate the loading applied by the connection strap on the base of the SDCA.

Table 2-1: Shaker Rack Mass

Component	Units	Qty	Calculation / Notes	Total (kg)
Shaker Rack	Each	1	Steel mass = 7,850 kg/m^3 Total steel = 0.0168m^3	132kg
Filter Bag	Each	168	1kg per bag	168kg
Dust per Bag	Each	168	9kg per bag	1,512kg
Total Mass				1,812kg

2.3.3 Mt Piper Fabric Filter Operation

The fabric filter plant is designed to reduce PM in the flue gas by passing the dirty gas into hoppers and thence through filter bags suspended above them. Heavier particles are deposited into the hoppers, while the lighter particles remain entrained inside the filter bags. The cleaned gas then passes to the stack (Howden, 1979).

Shaking Frequency and Duration

As dust particles become entrained on the inside of the fabric the differential pressure (DP) across the cell rises, and hence the plant DP rises, and the cell must be cleaned in order to keep the cell in operation. The cleaning is achieved by a shaker mechanism, which shakes the bags and causes the entrained dust to fall into the hopper. The dust is removed by an air slide disposal system. The cleaning can be achieved in three modes:

1. Automatic – Governed by peak plant DP and is the usual mode of cleaning
2. Non-Automatic – Allows the operator to select the level of cleaning, with up to three cells cleaned concurrently, once cells are cleaned they are returned to automatic mode
3. Manual – Individual cells are taken out of service and manually cleaned, whilst the Automatic and/or Non-Automatic modes continue. Once cells are manually cleaned they are returned to usual service

As the utilization of the Non-Automatic and Manual modes is a sequencing control, and not something that impacts the physical operation of the plant, additional detail regarding the operation of these modes is not relevant to this paper.

With the Automatic cleaning process, the overall plant differential pressure level establishes the rate of cleaning to be performed by governing the cell cleaning starting interval (t_s) used. The t_s is the period from the start of cleaning of one cell to the start of cleaning of the next.

Three levels of DP and four cell cleaning starting intervals are pre-selected and programmed into the control system. The most suitable cleaning rate is selected automatically, depending on the peak plant DP, which is monitored continuously. The control system always checks for the highest DP first.

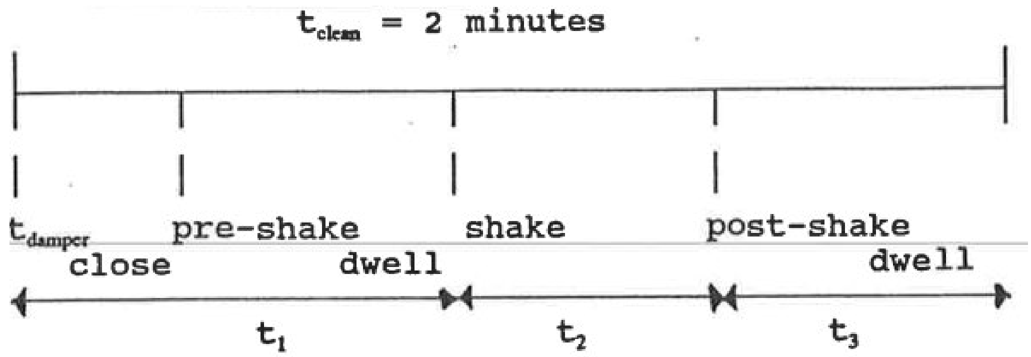

Figure 2-7: Cleaning time per cell (Howden, 1979)

Figure 2-7 shows the typical cycle for cleaning each cell and is based on the following equation:

$$t_{clean} = t_1 + t_2 + t_3 = 2\ minutes = Cleaning\ time\ per\ cell$$

Based on current operation, the value for $t_2 = {\sim}8\ seconds$, so the remainder of this 2 minute cycle is pre and post shake dwell, which is a pause in operation of the machine, allowing airborne dust within the cell to settle in the below hopper.

Sequencing and durations of cleaning cycles are based on variances in the DP within the cells.

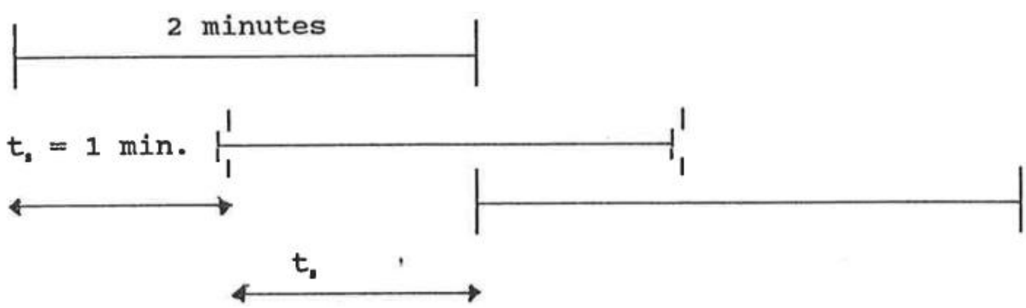

Figure 2-8: Two Cell Cleaning Cycle (Howden, 1979)

Figure 2-8 shows the sequencing of 2 cell cleaning cycles, which are initiated when DP is greater than or equal to 1.7 kPa. This increased frequency of cleaning cycles is to expedite the cleaning of fabric filter bags, as the increased DP indicates that there is an excessive amount of dust entrained on the fabric.

When DP is below 1.7 kPa, but greater than or equal to 1.3 kPa, the cycle shown in Figure 2-9 is initiated, where $t_s = t_{clean}$ and cleaning cycles occur consecutively.

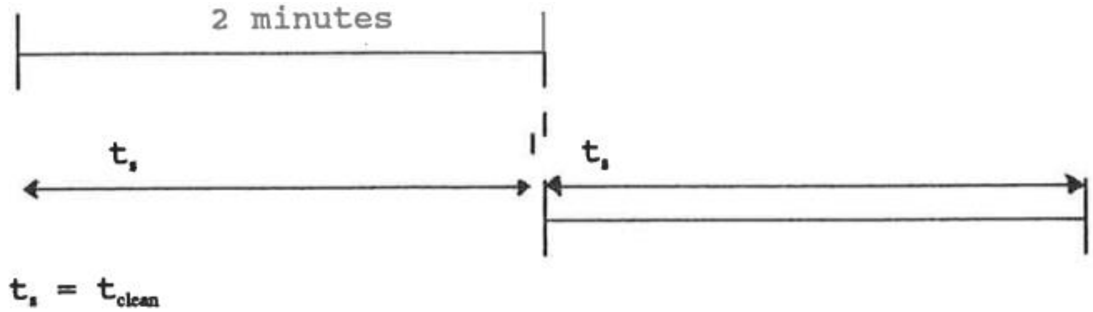

Figure 2-9: One Cell Cleaning Cycle (Howden, 1979)

The next cycle cleaning range occurs when DP is greater than or equal to 0.8 kPa, but below 1.7 kPa, when this cycle is initiated $t_s = 4\ minutes$. Finally, for DP values below 0.8 kPa, a cycle of $t_s = 6\ minutes$ occurs.

Once t_s has been selected, cleaning takes place on those cells which are available to be cleaned, i.e. have shaker motor drive available and both inlet and outlet dampers open. The cell selection sequence is depicted in the following image.

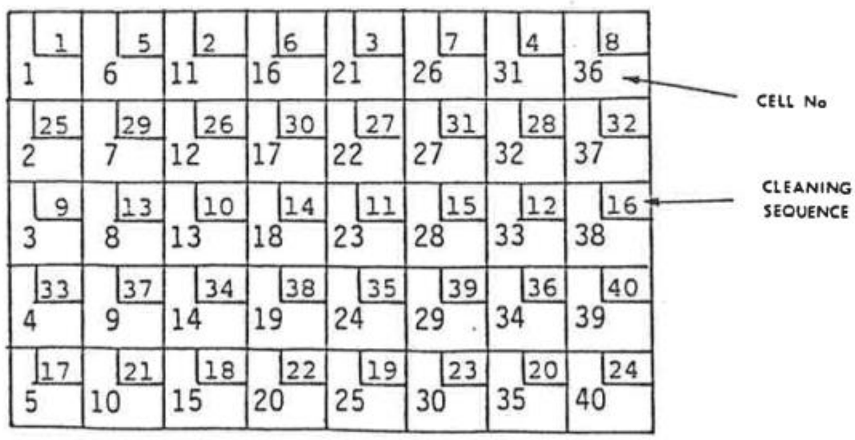

Figure 2-10: Sequence of Cell Cleaning (Howden, 1979)

The sequencing shown in Figure 2-10 relates to one of the two boilers at MPPS, in total there are 80 cells each containing 8 SDCA's. Each set of 8 SDCA's are assembled in 4 pairs of 2, and contain one SDCA connected to 160 filter bags, with the other SDCA connected to 168 filter bags. The cell configuration is described in Section 2.3.2 Shaker Mechanism Componentry and Technical Data.

Under typical operating conditions, cycles of $t_s = 6\ minutes$ occur, with an increase in frequency only initiated as DP increases. For the purpose of modelling the frequency each SDCA shaking cycle, $t_s = 6\ minutes$ will be allowed.

For each 40 cell unit experiencing a shaking cycle of $t_s = 6\ minutes$, the total time taken to complete one cycle of shaking for the one unit is 240 minutes. Therefore each SDCA experiences 8 seconds of shaking per 240 minute cycle.

An indicative periodic usage for the purpose of modelling the performance of existing SDCA's and estimating potential maintenance costs is as follows:

- Time per annum: $(24\ hours\ x\ 60\ minutes\ x\ 365\ days) = 525{,}600\ minutes$

- Number of 240 minute shaking cycles: $\frac{525{,}600}{240} = 2{,}190\ cycles\ per\ annum$

- Allowance for maintenance downtime: $10\%\ x\ 2{,}190 = 219\ cycles$

- Annual shaking cycles: $n_{annual\ shaking\ cycles} = 2{,}190 - 219 = 1{,}971\ per\ annum$

Based on an 8 second shaking duration for each SDCA per cycle, the total shaking time per annum for each SDCA is 15,768 seconds or ~263 minutes.

Drive Motor / Shaft Assembly

As noted in Figure 2-11 extracted from Howden design drawing 7001-0701, the 5.5kW, 960 rpm shaker motor powering the SDCA powers a 150 diameter pulley, which in turn drives a 400 diameter pulley connected to the SDCA drive shaft. Each cell contains one motor driving the 4 pairs of SDCA's, each pair positioned at a separate 90° timing interval to stagger the impact of SDCA's motion on the drive shaft.

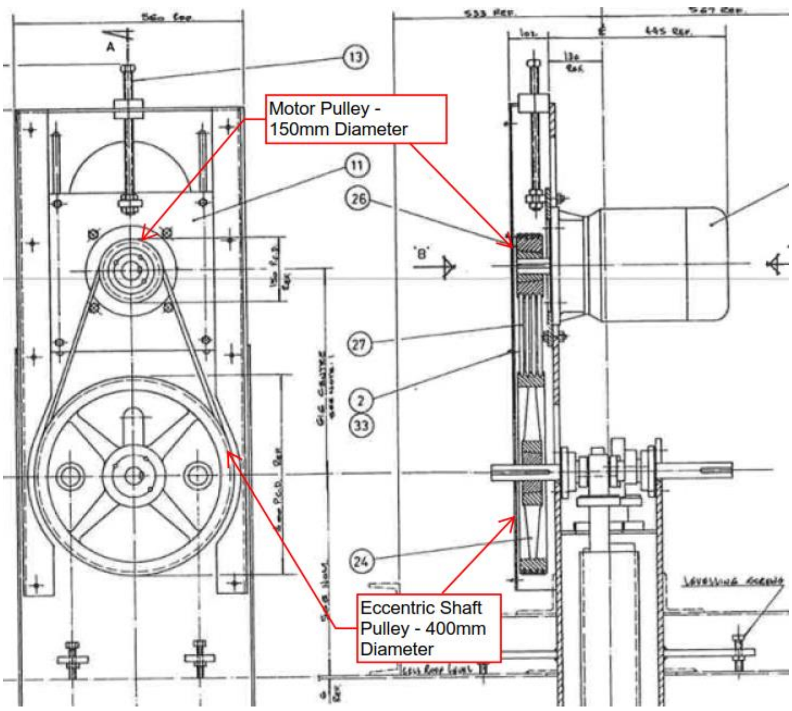

Figure 2-11: Shaker Drive Assembly (Howden, 1979)

Each revolution of the 400 diameter pulley represents one revolution of the eccentric drive shaft, which is connected across the four pairs of SDCA’s contained within each cell. Each pair of SDCA’s is driven by an individual eccentric shaft as denoted in the above shaker mechanism assembly taken from Howden design drawing 7001-0701.

The eccentric shaft/s (Intermediate and Drive versions shown in Figure 2-12), are attached to the top of each pair of SDCA’s by the shaker drive assembly and coupled to the shaker motor drive shaft/s by keys position at the keyway at each end.

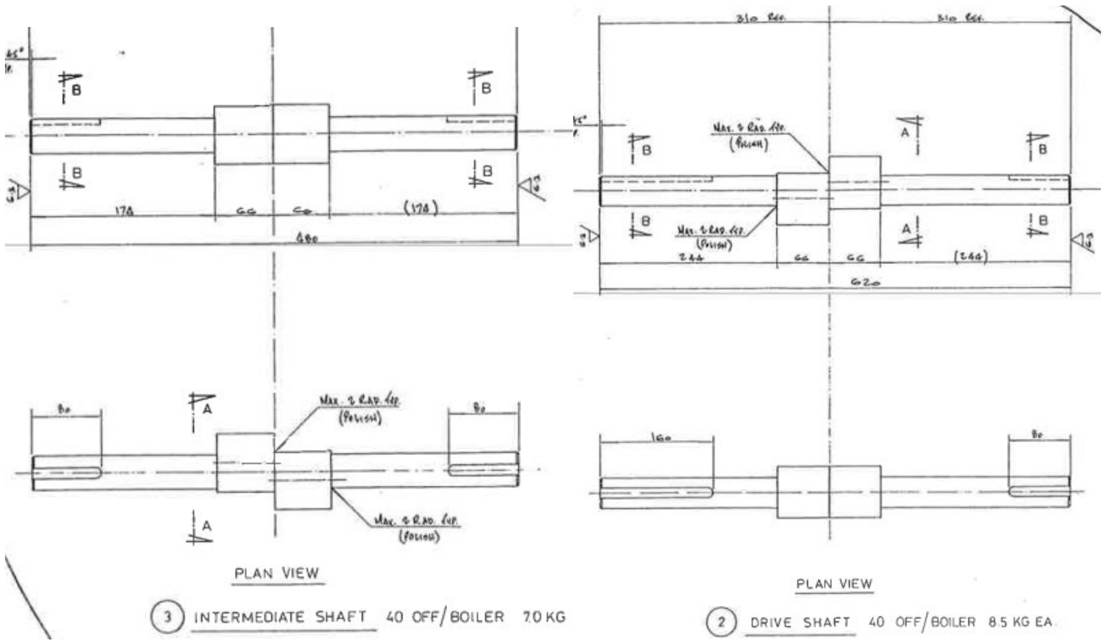

Figure 2-12: Intermediate and Drive Shafts (Howden, 1979)

The drive shaft for each cell rotates each of the 4 eccentric shafts, with each eccentric shaft subject to a differential timing position at 90° intervals from the adjacent eccentric shafts in the following configuration, positioned far side to near side in each cell:

- End shaft – Far side drive: 270° timing

- Intermediate shaft: 180° timing
- Drive shaft: 90° timing
- End shaft – Near side drive: 0° timing

Therefore, when the End Shaft – Near Side Drive is at the 0° location, the above details the locations of the other shafts at that instant.

Flue Gas – Temperature and Particle size

Temperature can impact the performance of steel and should therefore be a consideration in this analysis. As noted by Askeland and Phule (2008), both fatigue life and endurance limit decrease as a material's temperature increases. The material can be further impacted when exposed to large variances in temperature, which is the case with the SDCA's particularly when transitioning between operations and maintenance.

As the fabric filter is downstream from the boiler, the flue gas that is being filtered has the potential to reach temperatures that could potentially impact the performance of the steel componentry. Further, there is also the potential for abrasive wear within the fabric filter.

From the Howden Fabric Filter O&M Manual (1979), there are indicative values provided for the flue gas, including:

- Dust sizing: Median particle 5 - 25µm
- Dust bulk density: 500 kg/m^3
- Maximum flue gas temperature in Fabric Filter: 120°
- Temperature when undergoing maintenance: Ambient

Detail provided from MPPS operations indicate that the range of temperatures experienced in the fabric filter are as follows:

- Minimum Temperature: 109°
- Average Temperature: 112°
- Maximum Temperature: 120°

Documented detail regarding the rate of wear experienced through abrasive contact with dust is limited, however this can be verified through inspection of failed shaker arms. It should be noted that the SDCA's are painted during the fabrication process, however the coating used is for resistance to corrosion only, for the purpose of protecting the steel whilst in storage, prior to use. As many of the failed components still retain much of their painted coat, it is assumed that abrasive wear is negligible.

2.3.4 Maintenance Requirements

Upon reviewing the Howden Fabric Filter O&M manual (1979), with the exception of undertaking periodic inspections, there is limited detail specific to maintenance of the SDCA, rather a focus on the ancillary components that are utilized in supporting and driving the frame.

Other literature detailing Fabric Filter maintenance, such as the US EPA O&M manual for Fabric Filters (1988), detail an inspection regime for shaker-type fabric filters, however as with the Howden O&M manual, do not detail specific maintenance activities relating to the SDCA, aside from undertaking inspections.

The main variance between the Howden and US EPA O&M manuals is the frequency of inspections, with the Howden O&M manual calling for a six-monthly inspection of all shaker mechanism components with the exception of the drive belt, whereas the US EPA O&M Manual calling for a greater frequency of most inspections.

Figure 2-13 and subsequent maintenance detail, extracted from the Howden O&M manual, relate to the SDCA and ancillary componentry critical to the operation and functionality of the SDCA.

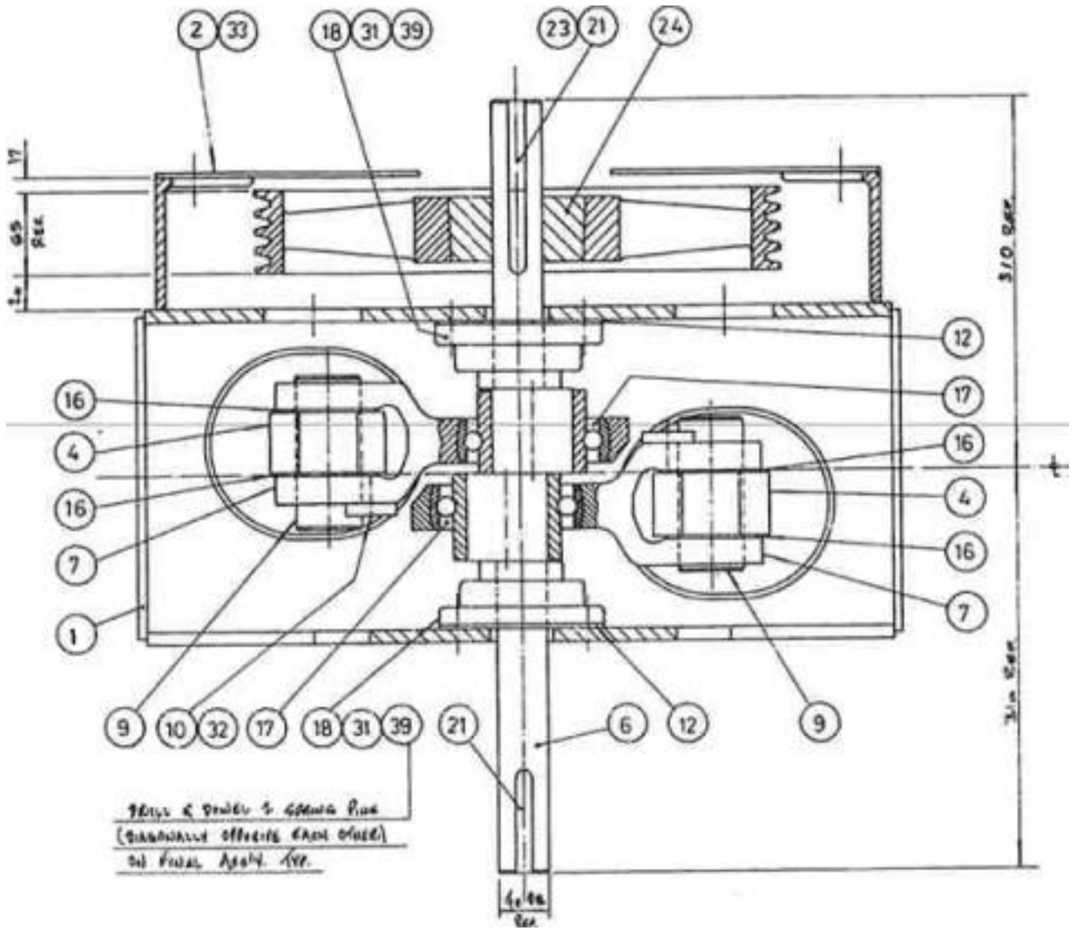

Figure 2-13: Shaker Drive Assembly (SDA) – Plan View (Howden, 1979)

The SDA, as shown in Figure 2-13, impacts the performance of the SDCA, as it provides the motion in the SDCA. Following are details of components and associated maintenance requirements critical to its operation (All are subject to 6 monthly inspection unless otherwise noted):

- Item 1: Shaker Drive Frame – Housing that is positioned around SDCA's and SDA, requires inspection only
- Item 4: SDCA – Top of the SDCA structure (Full SDCA structure noted in below image), secured between connecting rod yoke by connecting rod pin. Inspection involves 1 minute local operation, followed by inspection for wear / damage.
- Item 6: Eccentric Shaft – Subject to 1 minute local operation / inspection, replace when shaft found to rotate around bearing inner race
- Item 7: Connecting Rod – Replace when bearing is loose around spherical seat or if play exists in the machine bored yoke
- Item 9: Connecting Rod Pin – Replace when scored or surface finish is rougher than 0.4μm
- Items 16 and 17: Bearing – As bearings are designed to be sealed for life, they should be replaced when dust seals are broken; loss of lubrication noted; and/or collapsed cages / balls identified
- Item 18: PCD 400 Pulley / Wedge Belt – Subject to 1 minute local operation / inspection, replace when one or two become worn, cracked or stretched. Monthly inspection on tension, which is required between 35 – 38N
- Other items shown include, items 31, 32, 33 and 39 are all fasteners, item 10 is a keeper plate, item 12 a bearing packer, item 16 a thrust washer and item 21 a key. All are subject to six monthly inspection and replaced if signs of wear are identified.

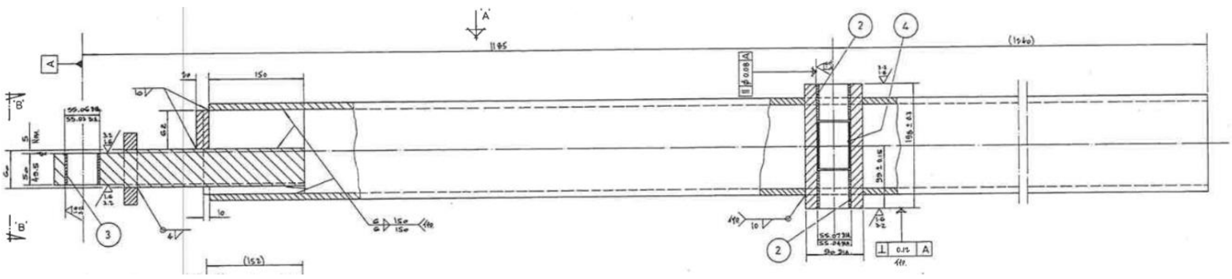

Figure 2-14: Shaker Drive Crank Assembly (SDCA) (Howden, 1979)

The SDCA noted in Figure 2-14 contains the main crank section along with the following items, also requiring 6 monthly inspections:

- Item 1: SDCA – As noted in item 4 above, inspection involves 1 minute local operation, followed by inspection for wear / damage.
- Items 2 and 3: Bush – Replace when changing pins, or if PTFE anti-friction coating has worn through.
- Item 4: Pipe spacer – Visual inspection when replacing bushes / SDCA

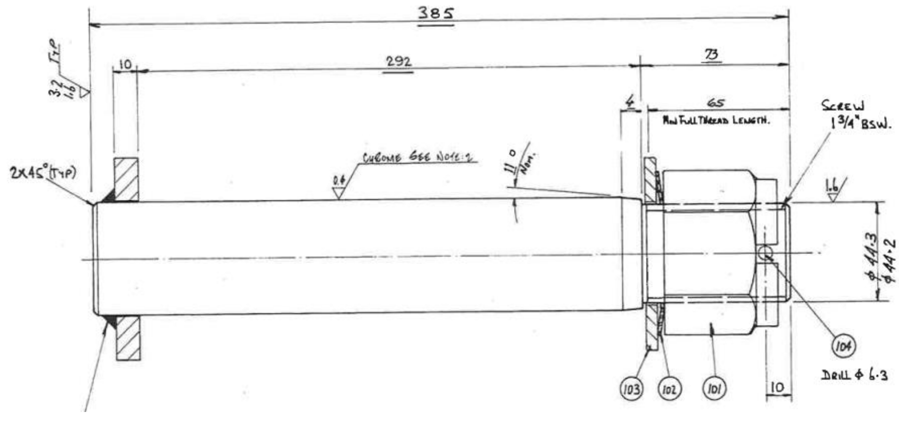

Figure 2-15: Pivot Pin (Howden, 1979)

The pivot pin shown in Figure 2-15 provides the connection between the shaker frame and the SDCA, it is the centre point of the sine wave motion generated by the SDA. Maintenance includes:

- Pivot Pin – Periodic inspection for wear, replacement when surface finish is rougher than 0.4 µm

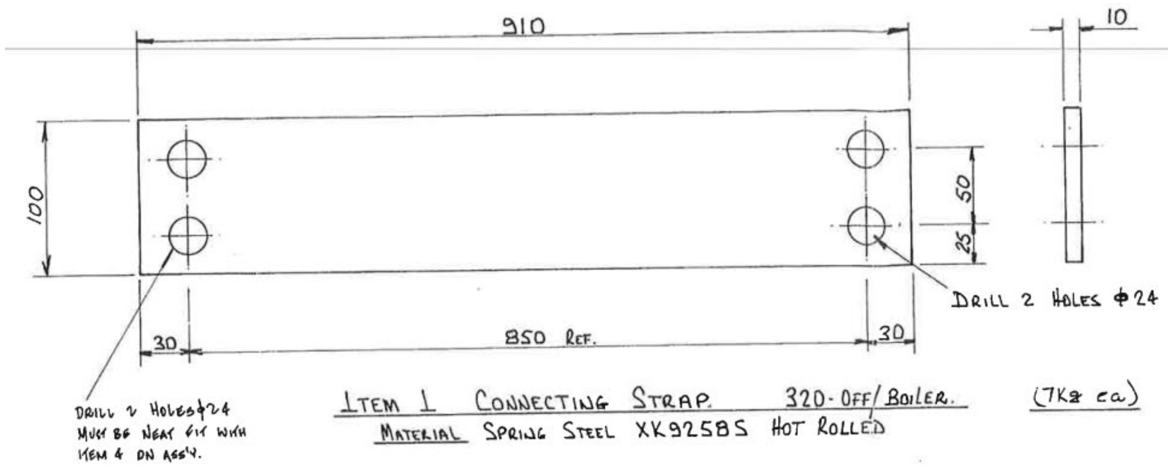

Figure 2-16: Shaker Connection Strap & Bolt Detail (Howden, 1979)

The shaker connection strap shown in Figure 2-16 transfers the force generated in the SDCA to the rack containing the fabric filter bags. Maintenance of the shaker connection strap includes:

- Connection Strap – Periodic inspection to verify bolt attachments are connected and strap has not fractured

Aside from the requirement to inspect on a six-monthly basis, there is no data provided regarding the suggested maintenance should a fault with the SDCA be identified. Upon inspection, the SDCA will show signs of failure either by being fractured or showing signs of fatigue / work hardening / cracking in the steel. As there is no specific directive on the SDCA maintenance methodology, it is assumed the OEM, JHA, intended that the asset owner would undertake SDCA maintenance based on the following philosophies:

1. Operate to failure – If indications of failure were identified in the SDCA, continue operation, replacing only once failure occurs
2. Replacement once likely failure identified – Pre-emptive replacement of SDCA's showing signs of fatigue / cracking, replacement of all SDCA's that have fractured
3. Repair – Perform modifications to SDCA's where they have either fractured or show signs of fatigue / cracking / work hardening

The maintenance processes currently adopted at MPPS are discussed in Chapter 3.2.

2.3.5 Performance History

In reviewing available literature on the SDCA, I was unable to source any information on previous operational performance and failure modes. There is also limited documentation on the SDCA performance at MPPS, other than through speaking with operational personnel.

The performance history detail obtained from discussions with MPPS operations personnel is as follows:

- The SDCA's have had a history of failing since operation at MPPS commenced in 1994
- SDCA's have on average 5 years design life when constructed in accordance with the original design, however there are no records tracking this performance
- The specified SDCA design has required modification to the specified 152 x 152 x 9.5 section as this is no longer a standard size Square Hollow Section (SHS)

- During the history of MPPS there has been several design iterations implemented, however detailed tracking of the performance of these iterations is limited
- MPPS have operated under a run to failure model, whereby SDCA's are changed out once failed or if there is visible signs of imminent failure apparent
- Many of the recent failed SDCA's are stockpiled on site, however there is no method established for tracking their service life and location in the fabric filter
- The shaker frame that houses the SDCA's and supports the pivot pins also can experience cracking when the SDCA fails
- Failure of SDCA's is usually identified aurally by personnel outside the fabric filter, the loose sections of steel can be heard impacting other steelwork
- There are some SDCA's from the original build that are still in operation

2.3.6 Design Iterations

As noted above there has been several design iterations of the SDCA performed at MPPS, however the recorded detail associated with these iterations is limited. They have often been based on a visual inspection of previously damaged SDCA's, with modifications driven by an attempt to reinforce failure areas. The other driver for these design iterations has been a change in the standard sizing of specified components.

In all instances, we can only estimate the service life duration as there have been no tracking of the life of these SDCA's. However, there are samples of several of the failed design iterations available, which will be utilised for modelling and assessment.

Detail of the review of these design iterations will be contained in the next chapter, Methodology.

CHAPTER 3: METHODOLOGY

The objective of the methodology section is to investigate the failure modes of SDCA's at MPPS, including both the proprietary design and any design iterations, with a view to determining the cause/s of these failures. These findings should then provide the basis for any proposed design modifications and / or process recommendations.

Following the identification of any prospective design modification/s in this chapter, the objective in the following chapters is to undertake both theoretical analysis and 3D simulation utilising the Element Method (FEM) with a view to establishing a correlation between key dynamic factors such as amplitude, frequency, acceleration and number of shakes with the longevity of the SDCA life, similar to the Fabric Filter Cleaning Studies undertaken by Dennis (1975), as described in Chapter 2.2.

If successful, the intent of this correlation is to develop a solution that is transferrable to fabric filter shaker infrastructure, across other industries outside of MPPS.

3.1.EXISTING SHAKER DRIVE CRANK ASSEMBLIES (SDCA'S)

As noted in Chapter 2.3.5, the data available detailing the historical performance of the SDCA's is limited. The only means of verifying the performance of the existing SDCA's is through assessing the failed members in conjunction with discussion with the operations and maintenance personnel on site.

This chapter details the information captured through this site inspection and discussion, including the failure characteristics of the proprietary design, as well as the various design iterations that have been developed and their subsequent performance.

3.1.1 Original Design Failures

The original design is fabricated in accordance with drawing 7001-0706 (Appendix D), the regions of the design where the greatest potential for stress concentrations are detailed as follows:

Pivot Pin Connection – The SDCA is constrained from translation by the pivot pin in x, y, z directions, however the SDCA does rotate around the pivot pin, driven by the motor, eccentric shaft and connecting rod at the top of the SDCA.

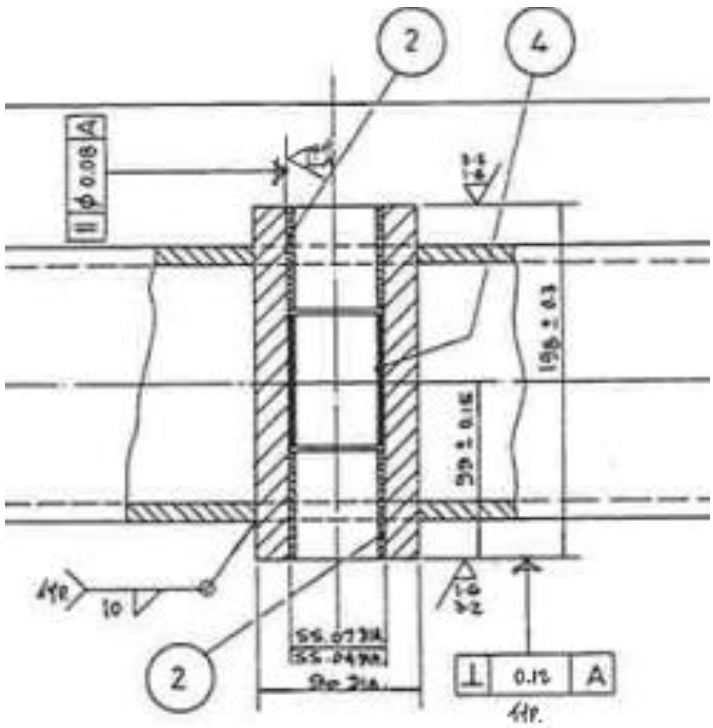

Figure 3-1: Pivot Pin Connection – Side View (Howden, 1985)

Figure 3-1 shows the pivot pin penetration, where a 198mm long x 90mm OD, ~55mm ID boss is welded by 10mm fillet weld to the 152mm x 152mm x 9.6mm SHS. When assembled, 2 bronze bushes are inserted into the boss on either side (2), with a pipe spacer (4) separator.

Shaker Drive Connection / SHS Interface – The SDCA motion is driven by the connecting rod pin, which penetrates the SDCA at (3). The pin is connected on either side by the connecting rod yoke, which sits either side of the SDCA neck section, as noted in the below image. The connecting rod experiences both rotational and translational forces driven by the attached eccentric shaft and motor.

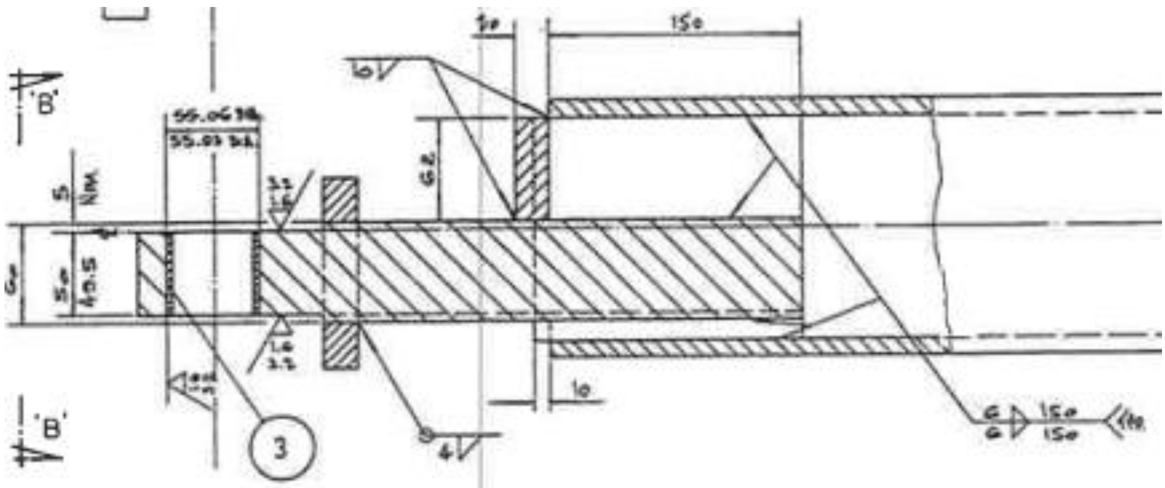

Figure 3-2: Shaker Drive Connection / SHS Interface – Side View (Howden, 1985)

Figure 3-2 shows the shaker drive connection consisting of a 60mm x 90mm plate (Main hatched section), which consists of a ~55mm penetration (3) for the connection rod, 114mm diameter x 10mm ring, connected by 4mm fillet weld and a 20mm thick plate with 10mm fillet weld connections to 3 edges of the end of the SHS and the shaker drive connection.

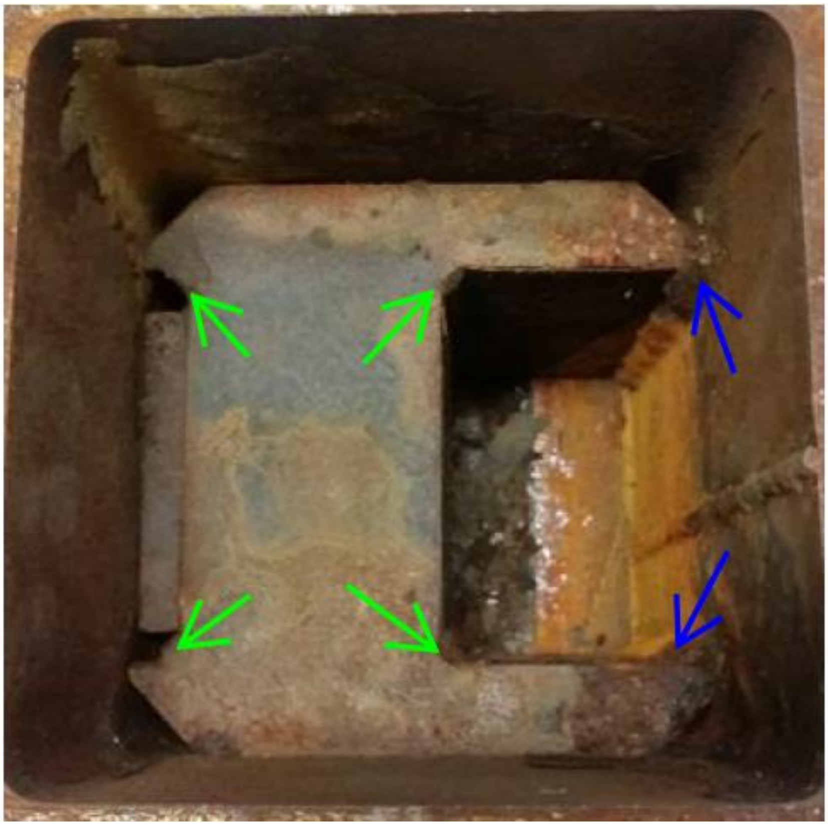

Figure 3-3: Shaker Driver / SHS Welded Connection

As shown in Figure 3-3, the shaker driver connection consists of 2 x 21.5mm thick x 133mm wide x 150mm long sections, with corner chamfers to allow for the inner radii of the SHS, that are welded in 4 locations (Green arrows) to the 60mm x 90mm section which is extends to the connection pin. The blue arrows show the location of the 2 x 150mm long x 6mm fillet welds, which form the connection between the shaker drive connection and the inner walls of the SHS.

Failure Examples

All recorded failures of the proprietary design have occurred in locations adjacent to the outside perimeter of the boss section which encompasses the pivot pin. Example 1 shown in Figure 3-4 shows failures typical to the proprietary design.

Figure 3-4: Original Design Failure – Example 1, Side View

With reference to Chapter 8 of *Fundamentals of Machine Component Design* (Juvinall & Marschek 2012), the locations identified by the green arrows are where the fatigue fracture has commenced, there is evidence of beach marks at both locations occurring at the region between the underside of the boss weld and the edge of the SHS. As the alternating stresses continued in this region, the cracks on each side of the SDCA continued to develop until fracture occurred, joining the two locations denoted by the green arrows.

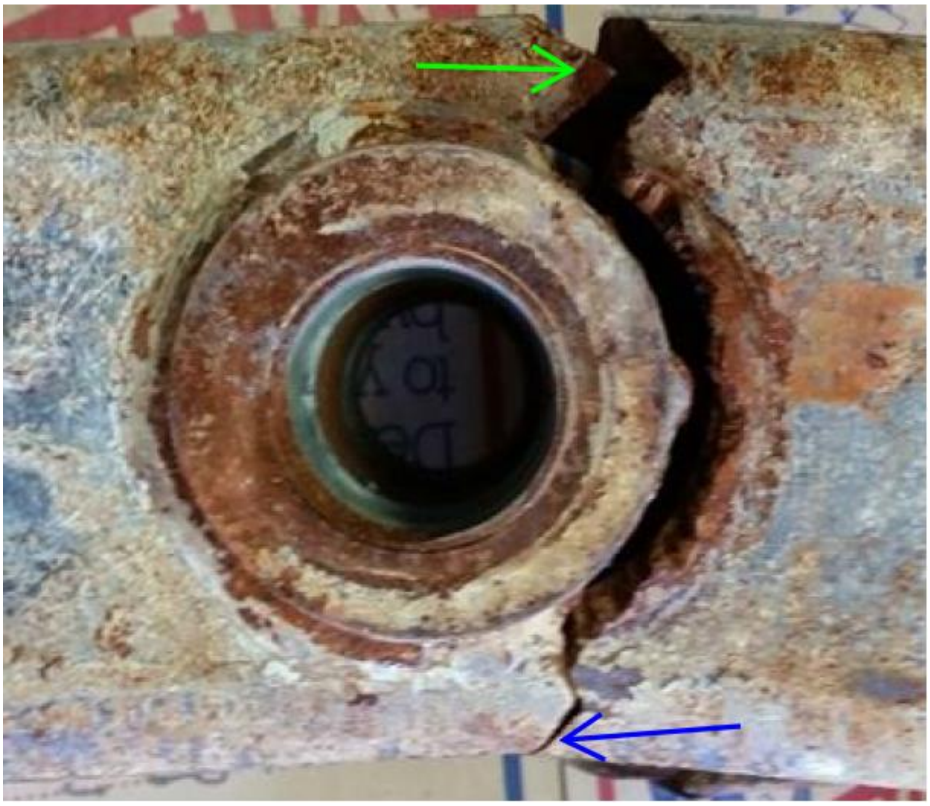

Figure 3-5: Original Design Failure, Example 1, Top View

Figure 3-5 is the top view of Example 1, the region shown by the green arrow shows a beach mark and is the initial crack site. Once fracture occurred, the crack also extended around the base of the weld join to the other side of the boss. In Example 1 the SHS has only partially fractured, however continued application of alternating stresses would see the remainder of the cross section of SHS fracture at the location denoted by the blue arrow.

In the following Figure 3-6 is Example 2, where the SHS on the lower side of the boss has completely fractured, there are visible beach marks (green arrow), there is a loose fit between the boss and the SHS (blue arrow), which would increase the stress concentration in this region in addition to impacting the effectiveness of the weld.

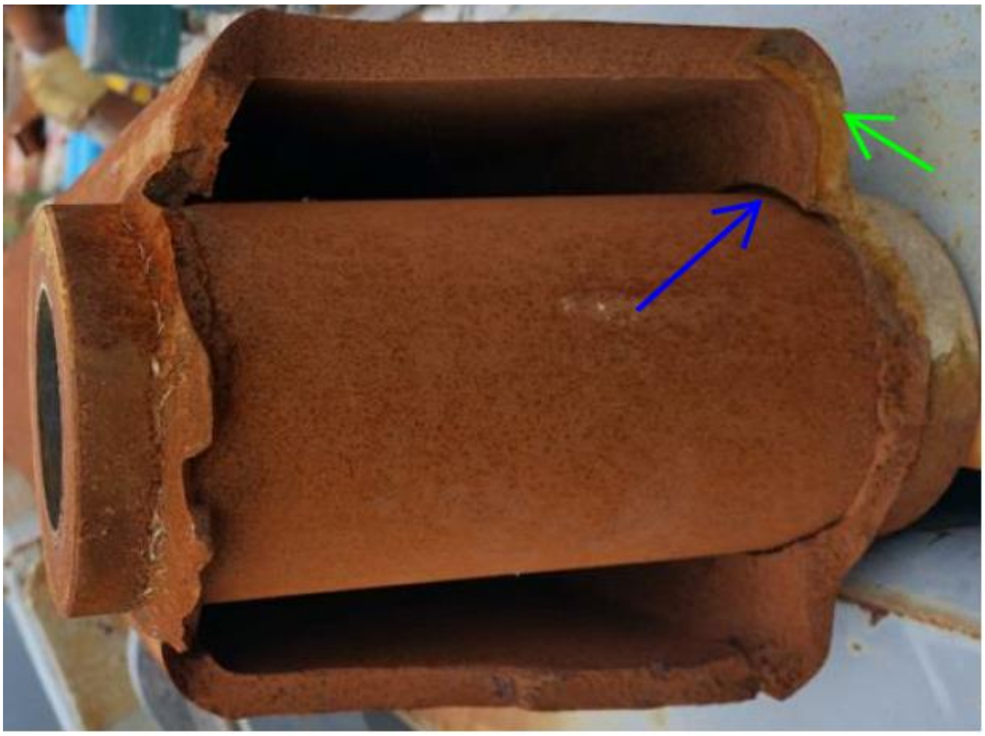

Figure 3-6: Original Design Failure, Example 2 – End View

As described in Figure 3.19 from *Engineering Drawing* (Boundy 2010), the fillet weld requires the two plates to be butted together, to allow the root penetration to provide consistent penetration along both legs and to the root. With the above, as there is no steel located at the root, this likely generates a significant stress raiser.

Figure 3-7 shows Example 3, where an SDCA that has been removed from service prior to fracture is shown.

Figure 3-7: Original Design Failure, Example 3

As noted by the blue arrow, a fatigue crack has commenced forming in a similar location to Examples 1 and 2, where it is proceeding to spread along the SHS towards the other side of the boss. When undertaking a visual inspection of operational SDCA's, this crack is an indicator that the SDCA is about to fracture and therefore requires replacement.

Several of the failed SDCA's show evidence of insufficient weld penetration, with fractures often passing through the weld at the same trajectory as the boss (refer green arrow in Figure 3-8), indicating a lack of weld penetration.

Figure 3-8: Original Design Failure, Example 4

As noted by M Cozens (2017) in his article *Fillet Welded Joints – A Review of Practicalities,* fillet welds require a higher heat input than butt welds, with less skilled welders this can lead to a lack of penetration and / or fusion defects that cannot be detected by visual examination and other NDT techniques. Often welds produced are larger than they need to be or may be a poor shape which can adversely affect their service performance.

As noted previously, there have been no records kept of the specific performance of the original design. Whilst the majority of the 640 original SDCA's have failed, it should be noted that some of the original design SDCA's are still in operation, which could potentially indicate a quality control issue.

Based on the inspection of failed SDCA's, the contributing factors to failure include:

- Beach marks indicate strain hardening occurring within the weld region that is between the base of the boss on the adjacent side of the SHS
- Once initial failure occurs, the SHS fractures on one side and then joins with the corresponding region on the other side of the SHS
- The path of the fracture, which always runs along the weld, indicates a lack of weld penetration in many of the members

3.1.2 Design Iterations

During the course of MPPS's operation, there has been various attempts to modify the original design, driven by a change in the standard sizing of components and the continual failure of the SDCA's. These modifications were primarily introduced as an attempt to reduce the stress around the boss, by reinforcing or modifying components within the original design. Following is a summary of the various design iterations:

Design Iteration 1 – Modified SHS to 150mm x 150mm x 9mm

The original design specified using 152mm x 152mm x 9.6mm SHS, however the design was modified when this size was no longer available. The first iteration involved using the currently available 150mm x 150mm x 9mm, Grade 250 steel. There is no data recorded on the actual performance, however the feedback from operations personnel at MPPS is that this size appeared to fail faster than the original design.

Design Iteration 2 – Modified SHS to 150mm x 150mm x 10mm

The second iteration involved using 150mm x 150mm x 10mm, Grade 250 steel. The feedback provided by operations personnel, suggested that there was an improvement in longevity from the 9mm, however there is no documented evidence to substantiate this feedback. This is the primary design utilised currently, with the following design iterations fabricated for experimental purposes.

Design Iteration 3 – Weld 400mm plates across fracture zone

As it was noted that all failures were occurring around the boss location, the third design iteration involved reinforcing this region to attempt to reduce the stress concentration around the boss. Figure 3-9 shows an example of this design change:

Figure 3-9: Design Iteration 3 – 400mm Plate Locations

As shown by the green arrows in Figure 3-9, where the SDCA was removed prior to fracture, two 400mm x 150mm x 10mm sections of steel plate were welded circumferentially to the sides of the SHS, the plate centerline coinciding with the pin pivot centerline. The intent was to reinforce the region around the boss where fracture had occurred previously.

Figure 3-10: Design Iteration 3 – 400mm Plate Fracture

The result involved the primary stress concentration location moving from the now reinforced boss region to the welded join between the end of the 400mm plate and the SHS, which is shown in Figure 3-10. This failure location was on the edges of the plates that were below the pivot pin, towards the base of the SDCA. As with the other examples, there is no recorded data verifying these failures, however the feedback from operations personnel is that this design increased the failure rate.

Design Iteration 4 – Weld full SHS length plates to the SDCA

As the welding of 400mm plates to the sides of the SHS had shifted the primary stress concentration to the weld join between the pivot pin and the base of the SDCA, the theory for the next design iteration was to extend these welded plates to the full length of the SHS, thus removing the stress concentrations from the SHS cross section entirely. In the following Figure 3-11 is an example of this design iteration is shown.

Figure 3-11: Design Iteration 4 – Full SHS length plates

The green arrows show the extents of the welded plate, each plate was 2225mm x 150mm x 10mm and welded circumferentially to the non-pivot pin sides of the SHS.

As shown in Figure 3-12, this design iteration resulted in fracture at the drive connection, at the top of the SDCA.

Figure 3-12: Design Iteration 4 – Full SHS length plates, Drive Connection

As noted by the green arrow, a large area of beach marks exist, with subsequent failure straight through the 60mm x 90mm steel section, adjacent to the top of the SHS. Operations personnel at MPPS advised that this failure occurred faster than the other modes of failure. As this failure occurred near the top of the SDCA, it also damaged the shaker drive frame which houses the top of the SDCA's and supports the pivot pins.

Design Iteration 5 – Additional weld added to boss / SHS connection

Following the failure of the full length plates, the next iteration involved adding two additional weld runs to the existing fillet root run. The theory was to reinforce the stress concentration locally at the boss, however failure continued to occur in this region and there was no improvement to SDCA longevity noted.

Design Iteration 6 – Change from Grade 250 to Grade 450 Steel

MPPS are currently trialing the use of 450 Grade Steel in conjunction with Design Iteration 2. There is currently no data available on the performance of this iteration, however in reviewing this change in conjunction with the calculations in *Table 8.1 – Generalised Fatigue Strength Factors for Ductile Materials* (Juvinall & Marschek, 2012), an increase in the Ultimate Strength value correlates with an increase in the endurance limit. Therefore it is likely that whilst stress concentrations and failure mode will remain, the life of the Grade 450 SDCA will be greater than the Grade 250 SDCA.

Other Design Iterations

It should be noted that through discussions with MPPS operations personnel and inspection of the failed SDCA's, there are some additional iterations for which there is currently limited detail, which may however assist with future analysis and design considerations. An overview of these designs are as follows:

- The use of a Universal Column as a replacement to the SHS. The specifics of this design are not known, however it can be assumed that the pivot pin penetrates the web of the column, with a welded joint connecting the top of the universal column to the drive connection. The sizing of the universal column used is not known. Feedback from MPPS operations personnel is that a model similar to this was installed several years ago and may still be in operation.
- Additional plate 90mm x 150mm x 10mm welded in between the shaker drive connection and the SHS. This has been noted in some of the failed sections inspected, with the original design having a void in this area. There is no

information currently available on the impact of this section, however it should be noted that it has been identified on failed SDCA's.

The initial crack site of each of the design iterations has been around the welded stress raisers, with the fracture spreading through the parent material. In most of the design iterations, the attempt was to either relocate or reinforce the stress raiser, which in each instance has not improved the life of the SDCA's.

There is also some evidence of failure relating to quality assurance, with feedback that some proprietary SDCA's are still in service and the mode of failure indicating failings in the welding process.

To further verify the stress concentration impact in these design iterations, Chapter 4 contains detail from the FEM analysis of these designs.

3.1.3 Fabrication and Installation

Fabrication of the SDCA's is performed by an offsite workshop, with the extent of the QA being the provision of the original specified drawing 7001-0706 with any design iterations provided in a sketch, email or verbally.

A summary of the fabrication steps is as follows:

- **SHS Section** – Standard size SHS is cut to length, with 90mm cut out for boss penetration. 90mm OD boss section is positioned, with 10mm fillet weld applied to the boss and SHS on both sides. The pipe spacer is installed with bronze bushes on either side

- **Drive Mechanism –** 60mm x 90mm section cut from plate, with 20mm x 114mm diameter section with 60mm x 90mm cut out attached with 4mm welds. A 45° chamfer is applied to all longitudinal edges, then a 20mm x 45° chamfer applied to the top edges and a ~55mm diameter penetration for the connection pin
- **SHS / Drive Mechanism Interface –** The drive mechanism has two 21.5mm x 133mm plates attached with 4 off 6mm fillet welds 150mm along the drive mechanism, these then have a 15mm x 45° chamfer applied to the outer edges. This is then inserted 150mm into the SHS, with four further 6mm fillet welds applied to attached to the inside of the SHS. There is then a plate secured with 10mm fillet weld across the top of the SHS, around the perimeter of the 60mm x 90mm drive mechanism
- **Painting –** The assembly is given a thin corrosion resistant coating for storage

Total cost for fabrication and delivery to site of each SDCA is $1,000, consisting of approximately $100 in materials and $900 in labour.

3.1.4 Quality Assurance

The tracking of SDCA's from fabrication, to location of installation, service duration and failure mode would allow more targeted analysis of performance and assessment against a greater range of potential causes for failure. As ascertained from the investigation, there is no form of historical tracking of each SDCA fabricated and installed.

For the purpose of this dissertation it is assumed that the root cause of the failure of SDCA's is systematic to their design and is consistent to their use throughout the fabric filter. The following are considered potential contributing factors to SDCA life, which cannot be analysed with certainty based on the data available:

- Position of SDCA's relative to the gas flow, with some cells experiencing a greater frequency of shaking, due to being positioned in an area where a higher density of dust in the flue gas exists
- Variations in the forces applied to the SDCA's due to wear between components and alignment / installation issues local to each SDCA location
- QA inspection of fabrication and welding, with all SDCA's fabricated off site without any form of quality control, such as use of weld procedures, welder qualifications and NDT of welds
- Increase in frequency of failure due to change in quality of materials used, with no form of material tracking implemented to verify the steel complies with specifications
- Impact of failure of other componentry associated with the SDCA

There is scope for changes around the quality assurance process that could potentially assist with increasing the endurance limit of the SDCA's, this will be discussed further in Chapter 5.

3.1.5 Limitations of Investigation

There are various limitations in analyzing the root cause of the SDCA's failure, with many of those limitations noted in the above section 3.1.4. The main limitation is the lack of record keeping associated with historical failures, with limited failed components available for inspection, as the majority of components have been disposed of. Further, much of the background information in this dissertation is based on the verbal account of operations personnel.

3.2. MAINTENANCE METHODOLOGY

Critical to the SDCA design are the limitations in maintenance that can be undertaken whilst in operation. As the normal operating temperature is >100°, there is no opportunity to undertake maintenance whilst the plant is in service, with the requirement to shut down and isolate the cell for any maintenance works.

Given the fabric filter is filled with filter bags during operation, there is limited opportunity to visually inspect the plant without isolating and shutting down the cell. Therefore, maintenance activities outside of scheduled outages, which typically occur once every four years, is reactive to the aural feedback from a fractured SDCA impacting other steel within the fabric filter when the drive motor is engaged.

3.2.1. Current Maintenance Regime

Under normal operating conditions, the SDCA installation process typically involves the isolation of one cell where all damaged SDCA's or SDCA's with visual signs of cracking are replaced. As noted above, there is also a requirement for a four yearly scheduled outage, where the fabric filter is isolated completely and all cells undergo maintenance.

The crew for an SDCA replacement includes 2 x Rigger / Forklift Operator, 1 x Fitter, 1 x Confined Space Watcher, with works overseen by a supervisor. Additionally, the plant and equipment requirements include 1 x Forklift, 2 x Chain Blocks, 1 x Gantry Hoist and slings.

MPPS applies an ‘operate to failure’ maintenance regime, due to the labour costs incurred to repair the SDCA’s once fractured. Interestingly, BPS does repair and reinstate their SDCA’s where possible, which indicates that there are potentially variables between MPPS and BPS in considerations, such as:

- Proximity of workshop to fabric filter
- Transportation means between workshop and fabric filter
- Availability of boilermaker / welding resources
- Frequency of inspections, if a cracking SDCA is identified before fracture, there is greater scope to repair

Further analysis of the most effective maintenance regime is beyond the scope of this dissertation.

The optimum design should seek to minimize the maintenance requirements, with cost of materials minor compared to the labour associated with fabrication, repair and replacement.

3.2.2. Cost Analysis

Approximately 6 SDCA’s are replaced each day maintenance is performed, assuming that the cell/s have been isolated and there are no delays with availability to access the cell/s. Based on this, the cost to replace each SDCA is shown in Table 3-1:

Table 3-1: SDCA Daily Maintenance Cost

Resource	Qty	Hourly Rate (Cost)	Hours	Total Cost	Notes
Rigger	2	$85.00	10	$1,700	Rates include Overtime / Overheads
Fitter	1	$95.00	10	$950	
Confined Space	1	$75.00	10	$750	

Supervision	1	$110.00	10	$1,100	
Forklift	1	$15.00	10	$150	
Miscellaneous Tools / Equip	1			$150	Slings / Chain Blocks / Hoist maintenance
Total Cost				**$4,800**	**5 SDCA's**

As detailed in the above table, the cost for a crew to replace 5 SDCA's in one day is $4,800, therefore the estimated cost per SDCA is $960, however this is dependent on changing multiple SDCA's in one day, with cost per SDCA to increase if less required replacement.

Annually, the estimated number of SDCA's that require replacement is 100 per annum, or 5 per day for 20 days, thus equating to a total maintenance expenditure per annum of $96,000.

Allowing $100,000 per annum for 100 x $1,000 SDCA's as per chapter 3.1.3, this total annual expenditure for the fabrication and installation of news SDCA's is $196,000.

Additionally, there are costs incurred by the asset owner to coordinate the closure of fabric filter cells for maintenance and the oversight of these maintenance activities undertaken by contract personnel. Based on the 20 days estimated, allowing asset owner supervision at $100 per hour for 10 hours per day, equating to $20,000 per annum, which includes an allowance for the scheduling of works.

Therefore, total annum maintenance expenditure is $216,000.

3.2.3. Maintenance Constraints

As the SDCA is a fabricated steel section which is subjected to cracking and fracture, the maintenance activities include inspection, welding repair or replacement. For any maintenance outside of the schedule outage, there is no possibility of performing welding activities within the fabric filter as it is filled with fabric filter bags, which are flammable. Therefore, the maintenance options outside the scheduled outage involves the removal of the SDCA, then either the installation of a new SDCA, or the repair of the existing SDCA in the workshop, followed by reinstatement.

3.3. OPERATIONAL VARIABLES IMPACTING DESIGN

As noted in The Engineering Design Process (Ertas and Jones, 1996), the proposed design should seek to minimize parts required, use standard size materials, design to simplify fabrication, minimize the use of fasteners, minimize assembly directions, minimize handling and repositioning of parts and facilitate ease of installation and maintenance where possible. The aim is to minimize the labour requirements to fabricate and maintain the SDCA's, with materials relatively inexpensive to fabrication and labour costs.

As the operating conditions are in >100° typically, with periods of ambient temperature for maintenance, the materials used should be suitable to these temperatures, with minimal fatigue impact associated with temperature fluctuation.

The design should also be compatible with the intended operation of the existing drive motor, including being suitably functional when exposed to the specified cyclic conditions, such as frequency, amplitude, speed and duration.

3.4. PROPOSED SOLUTIONS & OBJECTIVES

Based on the review of design requirements, previous failures, operating conditions and maintenance requirements, the following proposed solutions have been developed with input from the maintenance personnel at MPPS, for consideration and further analysis in Chapter 4.

1. **Welding tapered plates around pivot pin –** A variation to design iterations 3 and 4, the intent is to spread the load from the stress concentration around the boss, to the remainder of the SHS, however where design iterations 3 and 4 failed to having a weld perpendicular to the longitudinal length of SHS, a tapered plate would provide a distribution of the weld stress concentration of a greater area
2. **Reduce wall thickness of pivot pin boss OD –** Would a reduction in the wall thickness of the boss from 90mm to a much smaller dimension to provide a greater region between the edge of the SHS and the weld, where the stress concentration exists
3. **Butt weld boss flush to SHS with separate spacers –** By changing the boss length to 150mm and butt welding it to the SHS, this may reduce the stress concentration experienced between the boss and the edge of the SHS. Include spacers on each side for the width of the boss ends removed to simulate the existing design
4. **Reduce the wall thickness of the pivot pin boss –** Verify if a reduced wall thickness of the pivot pin boss would increase life. There are no examples of failures where the boss has failed prior to the SHS and weld, therefore it’s endurance limit is likely much larger than that of the SHS / Weld section

5. **Use different materials –** As the material cost is significantly less than the labour cost, review if there are any materials available that provide a greater endurance limit, such as different grade steels or variants on the component size used.
6. **Combination of the above –** As most of the proposed solutions impact different aspects of the design, there is the possibility to combine some of these solutions in the final proposal.

Proposed Design Objectives – The method for assessing each of the above solutions involves initially undertaking a theoretical analysis with reference to fatigue life and stress concentration, with reference to textbooks such as Fundamentals of Machine Component Design (Juvinall and Marschek, 2012) and Roark’s Formulas for Stress and Strain (Young and Budynas, 2002). If following the analysis, the solution appears viable, then model the solution using the FEM, with a view to confirming its endurance limit and failure mode.

CHAPTER 4: RESULTS

To ascertain the current operating conditions for the SDCA, an analytical analysis in conjunction with finite element simulation has been conducted. The main objectives of this analysis are to determine:

- Forces applied
- Maximum stresses
- Stress locations
- Estimated fatigue life

Once these values have been determined, they will create the benchmark for the identification and analysis of any proposed design modifications.

4.1. THEORECTICAL ANALYSIS

The focus of the dynamic analysis is the motion generated from the eccentric shaft to the SDCA, which then acts around the fixed pivot pin, applying motion to the fabric filter shaker rack where the dust is dislodged. An overview of this motion is described in the Figure 4-1.

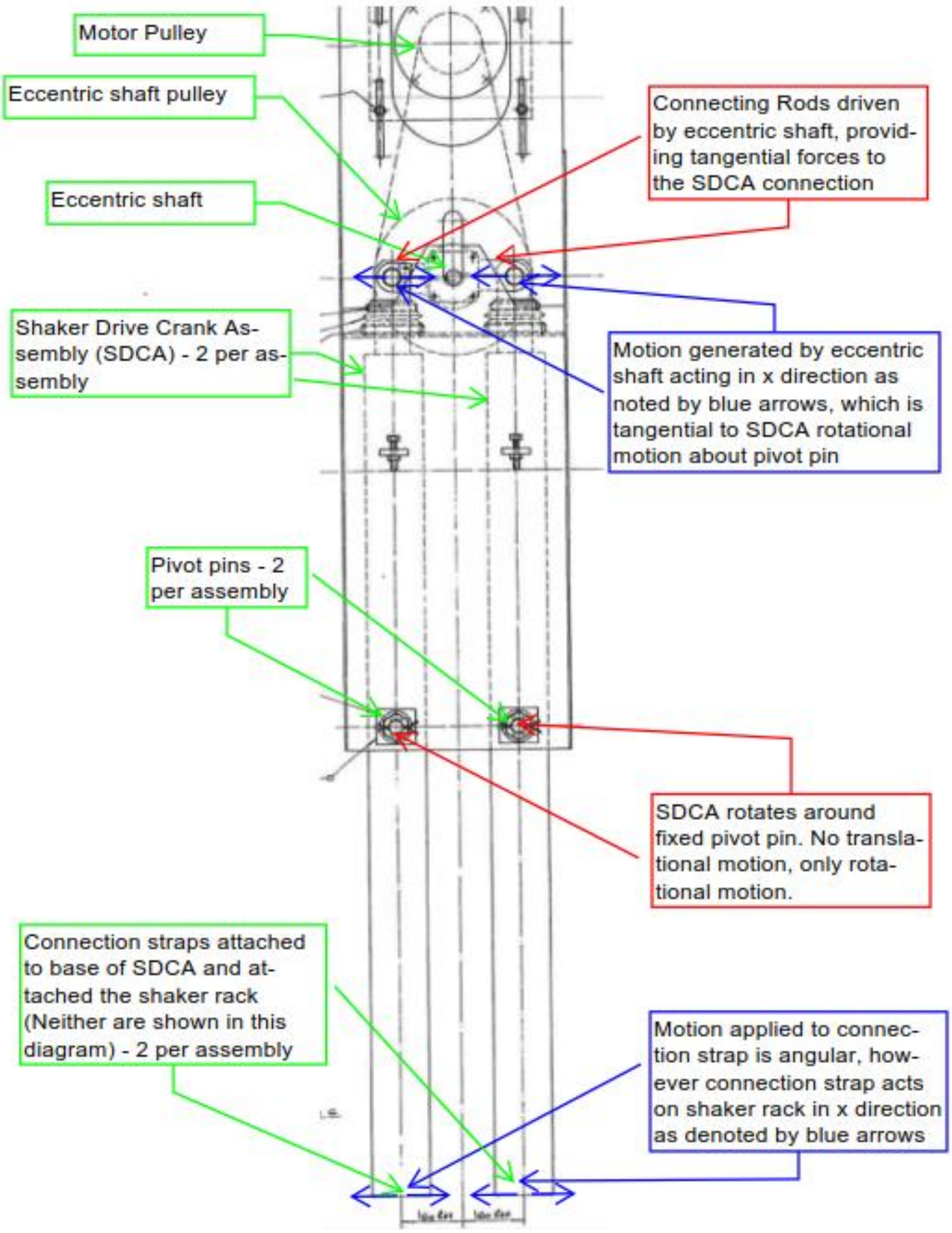

Figure 4-1: SDCA Motion Generated by Eccentric Shaft (Front View)

The motion commences with the motor pulley applying torque to the eccentric shaft pulley, which in turn drives the eccentric shaft. The eccentric shaft contains two offset shafts, each with an offset diameter of 0.01m, which provide the shaking action applied to the top of the SDCA's. Figure 4-2 provides a plan view of the above SDCA / eccentric shaft assembly.

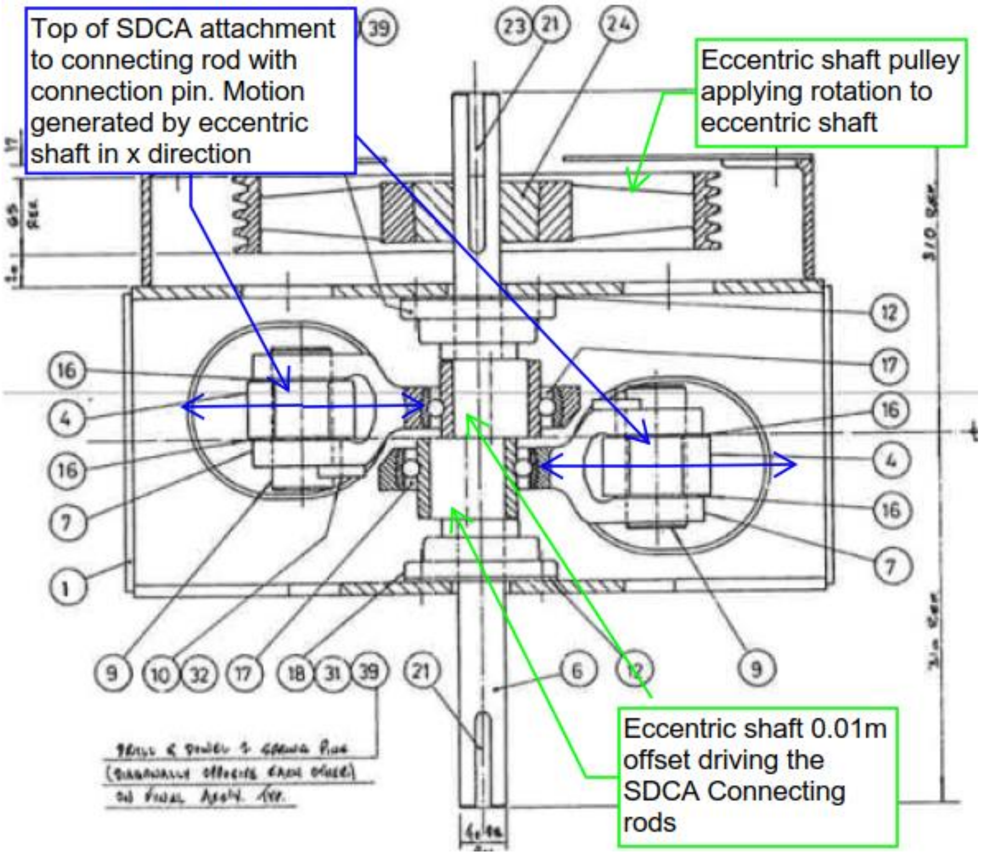

Figure 4-2: SDCA Motion Generated by Eccentric Shaft (Top View)

Here the eccentric shaft pulley drives the eccentric shaft, where the offset shafts apply oscillating motion to the connecting rods, which in turn provide motion to the SDCA via the connection pin.

4.1.1. Cycle Period

As detailed in Chapter 2.3.3, the MPPS analysis is based on a 240 minute cycle for the cleaning of all cells within a 40 cell fabric filter. Therefore, each cell has a 6 minute cleaning cycle (t_s), with 8 seconds of that 4 minutes cycle involving the engagement of the SDCA shaking mechanism (t_2), with time pre shake dwell (t_1) and post shake dwell (t_3) for settling of the dust.

Therefore, the shaking cycle period is as follows:

1. 400 diameter Eccentric shaft rpm (driven by 150 diameter drive motor pulley):

$$rpm_{eccentric\ shaft} = \frac{rpm_{drive\ motor} \times d_{drive\ pulley}}{d_{eccentric\ shaft\ pulley}}$$

$$rpm_{eccentric\ shaft} = \frac{960 \times 150}{400} = 360\ rpm$$

2. SDCA cycles per 8 second shaking period, which occurs every 240 minutes:

$$n_{oscillations\ per\ cycle} = \frac{360\ rpm}{60\ secs} \times 8\ secs = 48\ oscillations$$

3. As there are 48 cycles within each 8 second shaking duration, the period of each cycle is:

$$\tau = \frac{t_2}{n_{cycles}} = \frac{8\ seconds}{48\ cycles} = 0.1667\ seconds\ per\ oscillation$$

The motion generated by the eccentric shaft driving the SDCA maintains a constant oscillation throughout each 8 second period, with no variable speed at initiation of cessation of the cycle.

With reference to the eccentric shaft, as the eccentric radii are offset from the primary shaft by 0.01m, therefore the peak amplitude is:

$$A = Amplitude = 0.01m$$

The parameters for amplitude and number of shakes used at MPPS are similar to the results detailed in Figure 2.3 extracted from *Fabric Filter Cleaning Studies* (Dennis, 1975*)*, where ~50 was deemed the most efficient number of shakes per cycle.

4.1.2. Kinematic Motion Calculations

Utilising the known dimensions of the fabric filter components, the kinematic diagram shown in Figure 4-3 can be developed and used as the basis for calculating the relative motion between points. This figure is based on the eccentric shaft location of 90° relative to the centre of the shaft, with the locations of the associated componentry at this time step. Through identifying the relative location of components at this time step, it is then possible to identify the relative position of components with respect to time in 5° increments, with the calculation of the position of Point B for motion in the x and y plane with respect to time the objective.

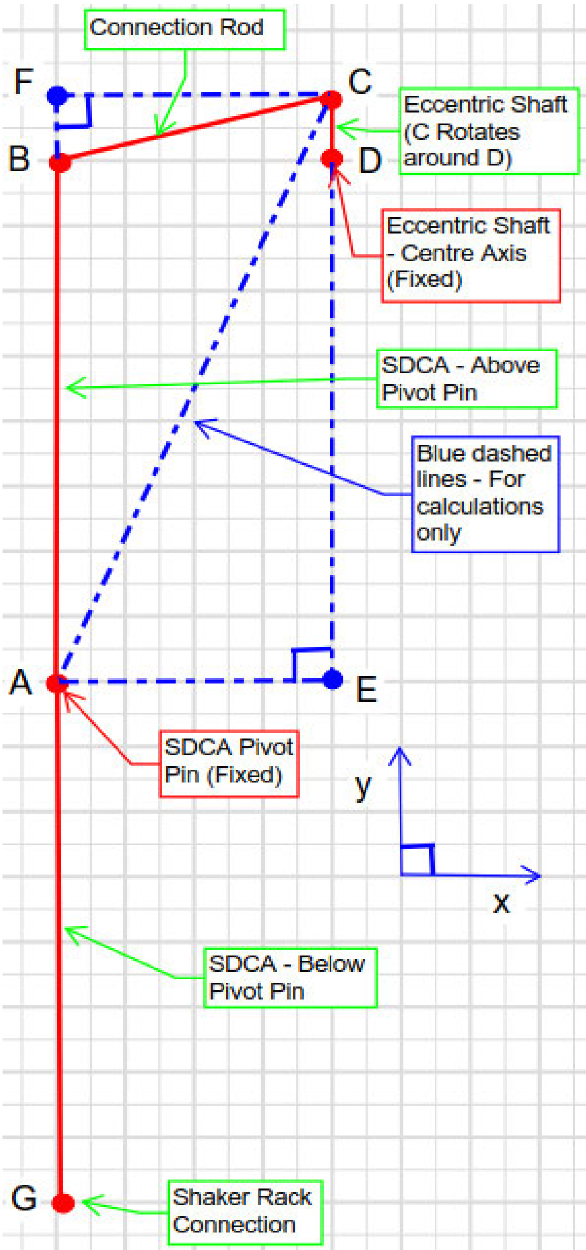

Figure 4-3: SDCA Kinematic Motion

The dimensions of the red lines are as follows, noting the diagram is not to scale:

- Eccentric Shaft (CD): 0.010m
- Connection Rod (BC): 0.150m
- SDCA Above Pivot Pin (AB): 1.185m
- SDCA Below Pivot Pin (AG): 1.285m

Additionally, the following points are fixed:

- Eccentric Shaft Centre Axis (Point D)
- SDCA Pivot Pin (Point A)

To establish the motion of the SDCA, the position of Point B relative to the fixed locations Point A or D is required. As Points A and D are fixed, the distance of A relative to D in the x and y plane are as follows:

- X direction (AD_X): -0.1497m
- Y direction (AD_Y): -1.1850m

For the purpose of the analytical analysis undertaken in Microsoft Excel, the time steps have been linked to the rotation of Point C about Point D, with increments of 5° utilised to calculate acceleration. As noted earlier in this chapter, each cycle is τ = 0.1667 seconds, therefore time steps are calculated as follows:

$$\left(\tau_{Step}\right)_5 = \tau\left(\frac{5°}{360°}\right) = 0.1667\left(\frac{5°}{360°}\right) = 0.00231\ seconds$$

For the provided kinematic motion diagram, where Point C relative to Point D is 90°, the corresponding time step is:

$$\left(\tau_{Step}\right)_{90} = 0.1667\left(\frac{90°}{360°}\right) = 0.0417\ seconds$$

Length CD = 0.01m, therefore the position of Point C relative to Point D in the x and y plane can be obtained at any given time step. At 90° the position of Point C relative to Point D is as follows:

- X direction (CD_X): 0.0000m
- Y direction (CD_Y): 0.0100m

Therefore a relationship relating the position of Point C relative to Point A can be calculated at this time step:

$$CA_X = CD_X - AD_X = 0.000\text{m} - (-0.1497\text{m}) = 0.1497\text{m}$$

$$CA_Y = CD_Y - AD_Y = 0.010\text{m} - (-1.1850\text{m}) = 1.1950\text{m}$$

The location of Point B can then be obtained through calculating the length of AC and utilising the sine and cosine laws to obtain the angles of triangles ABC and BCF at each time step.

The length of AC when Point C is at 90° relative to Point D is calculated as follows:

$$AC = \sqrt{(CA_X)^2 + (CA_Y)^2} = \sqrt{0.1497^2 + 1.1950^2} = 1.2043m$$

With lengths AC, AB and BC now known, the following angles at $\left(\tau_{Step}\right)_{90} = 0.0417\ seconds$ can be derived utilising the cosine laws:

$$\angle BAC = \cos^{-1}\left(\frac{BC^2 - AC^2 - AB^2}{-2 \times AC \times AB}\right) = \cos^{-1}\left(\frac{0.15^2 - 1.2043^2 - 1.185^2}{-2 \times 1.2043 \times 1.185}\right) = 7.1388°$$

$$\angle ABC = \cos^{-1}\left(\frac{BC^2 + AC^2 - AB^2}{-2 \times BC \times AB}\right) = \cos^{-1}\left(\frac{0.15^2 + 1.2043^2 - 1.185^2}{-2 \times 0.15 \times 1.185}\right) = 93.8225°$$

$$\angle BCA = \cos^{-1}\left(\frac{AB^2 - BC^2 - AC^2}{-2 \times AC \times BC}\right) = \cos^{-1}\left(\frac{1.185^2 - 0.15^2 - 1.2043^2}{-2 \times 1.2043 \times 0.15}\right) = 79.0387°$$

To assist with the application of the sine law for the angle calculation at each moment in time, the position of Point A and Point C with reference to Point E can be calculated:

$$AE = CD_X - AD_X = 0.000 - (-0.1497) = 0.1497m$$

$$CE = AB + CD_Y = 1.185 + 0.010 = 1.1950m$$

Using the sine law, angle ACE can now be calculated:

$$\frac{\sin(ACE)}{AE} = \frac{\sin(AEC)}{AC} \rightarrow \angle ACE = \sin^{-1}\left(0.1497 \times \frac{\sin(90)}{1.2043}\right) = 7.1388°$$

The right angle ECF is constant at any moment in time, with the sum of angles within ECF varying with each time step.

$$\angle ECF = \angle BCF + \angle ACB + \angle ACE$$

Calculating the unknown angle BCF at any given time step, provides the position of Point B relative to Point C, which in turn provides the position of Point B to fixed Point D, and subsequent position of the SDCA with respect to time. Therefore when Point C is at 90°, angle BCF is as follows:

$$\angle BCF = \angle ECF - \angle ACB - \angle ACE = 90.0000 - 79.0387 - 7.1388 = 3.8226°$$

Using the sine rule, the position of Point B relative to Point C in the Y plane can now be obtained:

$$BC_Y = \sin(BCF) \times \frac{BC}{\sin(BFC)} = \sin(0.0667) \times \frac{0.15}{\sin(90)} = 0.0100m$$

The position of Point B relative to Point C in the x plane can now be calculated:

$$BC_X = \sqrt{BC^2 - (BC_Y)^2} = \sqrt{0.15^2 - 0.01^2} = 0.1497m$$

As the position of Point C relative to fixed Point D is known, the position of Point B with respect to fixed Point D is now known:

$$BD_X = BC_X - CD_X = 0.1479\text{m} - 0.000\text{m} = 0.1497\text{m}$$

$$BD_Y = BC_Y - CD_Y = 0.0100\text{m} - 0.0100\text{m} = 0.0000\text{m}$$

Utilising the position of Point B in the x and y plane with respect to time, the rectilinear velocity can now be obtained by calculating the rate of change of position and time, with the delta the change from Point C being located at 85° to 90° relative to Point D (Noting that values obtained for the 85° time step are from the detailed calculations located in Appendix F):

$$v_{90} = \frac{\Delta s}{\Delta t} = \frac{(BD_X)_{90} - (BD_X)_{85}}{t_{90} - t_{85}} = \frac{0.0000 - 0.0009}{0.0417 - 0.0397} = -0.3754\ m/s$$

The tangential acceleration of Point B can then be obtained for the same time step:

$$a_{90} = \frac{\Delta v}{\Delta t} = \frac{(v_{BD})_{90} - (v_{BD})_{85}}{t_{90} - t_{85}} = \frac{-0.3754 - (-0.3704)}{0.0417 - 0.0397} = -2.1631 m/s^2$$

These above calculations note the use of values from Point B motion relative to fixed Point D, these are also relative to Point A which is also fixed. Point A is the SDCA pivot pin and the radial point from which the angular acceleration of Point B is calculated as follows:

$$(\alpha_B)_{90} = \frac{(a_B)_{90}}{r_{BA}} = \frac{-2.1631}{1.1850} = -1.8254\ rad/s^2$$

The corresponding angular acceleration at Point G can also now be calculated:

$$(\alpha_G)_{90} = (\alpha_B)_{90} \times \frac{r_{BA}}{r_{GA}} = -1.8254 \times \frac{1.1850}{-1.2850} = 1.8254\ rad/s^2$$

These formulas can now be applied to the complete 360° cycle of the eccentric shaft driving the motion of the SDCA (Points B and G) about the pivot pin (Point A), with the results detailed in Appendix F.

When applied to the 360° cycle of eccentric shaft rotation, in 5° increments, the angular acceleration about the pivot pin can be identified for each location of the eccentric shaft, or Point C relative to Point D.

The following graph shows the range of angular acceleration applied to the top (Point B) and bottom (Point G) of the SDCA.

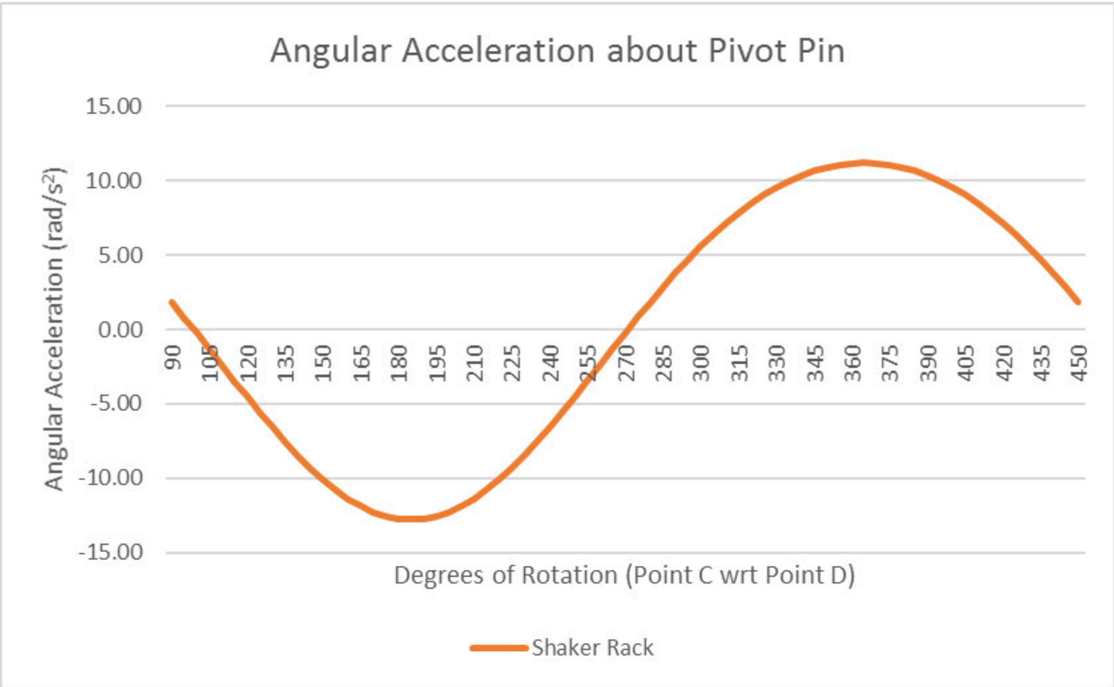

Figure 4-4: Angular Acceleration about Pivot Pin

As shown in Figure 4-4, the maximum angular acceleration is experienced when Point C is relative to Point D at angles 10° and 185°. The angular acceleration experienced at these angles are as follows:

- Point C at 10° relative to Point D: $(\alpha_G)_{10} = 11.16\ \frac{rad}{s^2}$
- Point C at 185° relative to Point D: $(\alpha_G)_{185} = -12.78\ \frac{rad}{s^2}$

The highest stress values applied to each side of the SDCA will be experienced at these locations of the eccentric shaft.

4.1.3. Mass Calculations

The proprietary design of the SDCA consists of all components being manufactured with 250 grade steel, which has a density (ρ) of 7,850 kg/m^3. With reference to the following SDCA loading diagram, there are 4 primary loads acting:

- Mass 1 (m_1): Shaker Drive Connection Assembly Point Load, consisting of various steel components that provide the link to the Connection Rod and form the top of the SDCA.
- Mass 2 (m_2): SHS above Pivot Pin Uniformly Distributed Load (UDL), consisting of SHS section above pivot pin.
- Mass 3 (m_3): SHS below Pivot Pin UDL, consisting of SHS section below pivot pin.
- Mass 4 (m_4): Shaker Rack Point Load, connected via steel strap to the base of the 60mm block located at the base of the SDCA

The mass moment of inertia calculations are based on the following assumptions:

- The shaker rack is a mass moment acting at the end of the shaker arm
- Moment caused by the boss encompassing the pivot pin is negligible
- The fabric filter shaker racks consist of either 160 bags or 168 bags, calculations are based on the loading associated with a 168 bag shaker rack
- Loading is based on each fabric filter bag containing 9kg of dust

- The variance in the centroid location for point loads contained within the Shaker Drive Connection Assembly due to material dimensional variances is negligible

Following are the SDCA mass moment of inertia calculations for each of the masses described above:

Mass 1 (m_1): SDCA – Shaker Drive Connection Assembly

The Shaker Drive Connection Assembly consists of various components that provide the link between the connection rod and the SHS. The volume of each of these components have been calculated from the dimensions provided in drawing 7001-0706 (Appendix D) and are detailed in Table 4-1:

Table 4-1: Mass 1 (m1) Volumes

Assembly Component	Volume (m^3)
Shaft (Minus 5mm Chamfer)	0.00196
114 Diameter Section	0.00200
Connection Rod Penetration	-0.00012
2 x 45° Chamfer	-0.00002
SHS Internal Plates	0.00036
SHS End Capping	0.00017
Total Volume (V_1)	0.00260

Total Mass (m_1) is therefore:

$$m_1 = \rho V_1 = (7850)(0.0026) = 20.04\ kg$$

The mass is acting at a central radius from the pivot pin, which is located at a radius (r_1) of 1.0325 metres from the centre of the pivot pin. Therefore, the mass moment of inertia is:

$$I_1 = m_1 {r_1}^2 = (20.04)(1.0325^2) = 21.37\ kg/m^2$$

Mass 2 (m_2): SDCA – SHS above Pivot Pin

The SHS above Pivot Pin is calculated on the 43 kg/m lineal metre rate of 150mm SHS over the 0.985m length of the SHS above the Pivot Pin centre axis. Therefore:

$$m_2 = \frac{m}{l} \times l_{SHS} = (43)(0.985) = 42.36\ kg$$

The mass is acting as a UDL across its total length, therefore the mass moment of inertia is:

$$I_2 = \frac{1}{12} \times ml^2 = \frac{1}{12}(42.36)(0.985^2) = 3.42\ kg/m^2$$

Mass 3 (m_3): SDCA – SHS below Pivot Pin

As with Mass 2, Mass 3 is calculated on the 43 kg/m lineal metre rate of 150mm SHS, however the length of the section is 1.285m. Therefore:

$$m_3 = \frac{m}{l} \times l_{SHS} = (43)(1.285) = 55.26\ kg$$

The mass is acting as a UDL across its total length, therefore the mass moment of inertia is:

$$I_3 = \frac{1}{12} \times ml^2 = \frac{1}{12}(55.26)(1.285^2) = 7.60\ kg/m^2$$

Mass 4 (m_4): SDCA – Shaker Rack Assembly

The Shaker Rack Assembly applies a point load to the base of the SDCA. The volume of the components have been estimated using the dimensions provided on drawings 7001-0700 and drawing 7001-0721 (Appendix D). Table 4-2 shows the estimated volumes:

Table 4-2: Mass 4 (m4) Volumes

Assembly Component	**Volume (m^3)**
Connection Strap	0.00091
Crank Block	0.00101
Shaker Rack	0.01680
Total Volume (V_4)	0.0187

In addition to the steel volume, an allowance for the mass of the 168 fabric filter bags (n_{FB}) is required as shown in Table 4-3:

Table 4-3: Fabric Filter Bag Mass

Fabric Filter Mass	**Mass (kg)**
Fabric Filter Bag (m_{bag})	1.00
Dust per bag (m_{dust})	9.00
Total Mass	10.00 kg

Therefore the total Shaker Rack Assembly Mass is as follows:

$$M_4 = \rho V_4 + n_{FB}\left(m_{bag} + m_{dust}\right) = (7850)(0.0187) + (168)(9 + 1) = 1{,}826.98\ kg$$

The mass is acting at the base of the SDCA, which is a radius (r_4) of 1.345m from the centre of the from the pivot pin. Therefore, the mass moment of inertia is:

$$I_4 = m_4 {r_4}^2 = (1{,}826.98)(1.305^2) = 3{,}111.40\ kg/m^2$$

4.1.4. Loading Calculations

Whilst the motion of the SDCA is generated by the eccentric shaft driving the connecting rod, which applies both force and torque to the top of the SDCA, the primary SDCA failure location is below the pivot pin, which is the focus of this analysis.

The motion below the pivot pin has a single moment input, where the SHS member is subject to the moment generated by the shaker rack mass moment of inertia and the angular acceleration generated by the eccentric shaft driving the connection rod, causing the SDCA to rotate around the pivot pin. A free body diagram detailing this moment is shown in Figure 4-5.

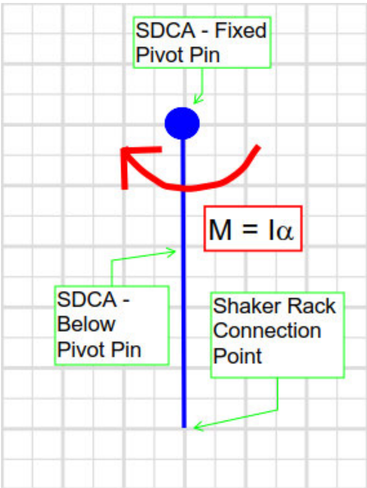

Figure 4-5: Moment – SDCA Shaker Rack acting about Pivot Pin

For the moment in time, where Point C is located 90° relative to Point D, this calculation is described with the following formula:

$$M = I_4(\alpha_G)_{90} = \left(3{,}111.40\,\frac{kg}{m^2}\right)\left(1.8254\,\frac{rad}{s^2}\right) = {\sim}5{,}700\ Nm$$

This moment is acting at the base of the SDCA, with stresses experienced throughout the SDCA oscillating in the x-plane. Figure 4-6 details the range of moments with respect to the angle of Point C relative to Point D.

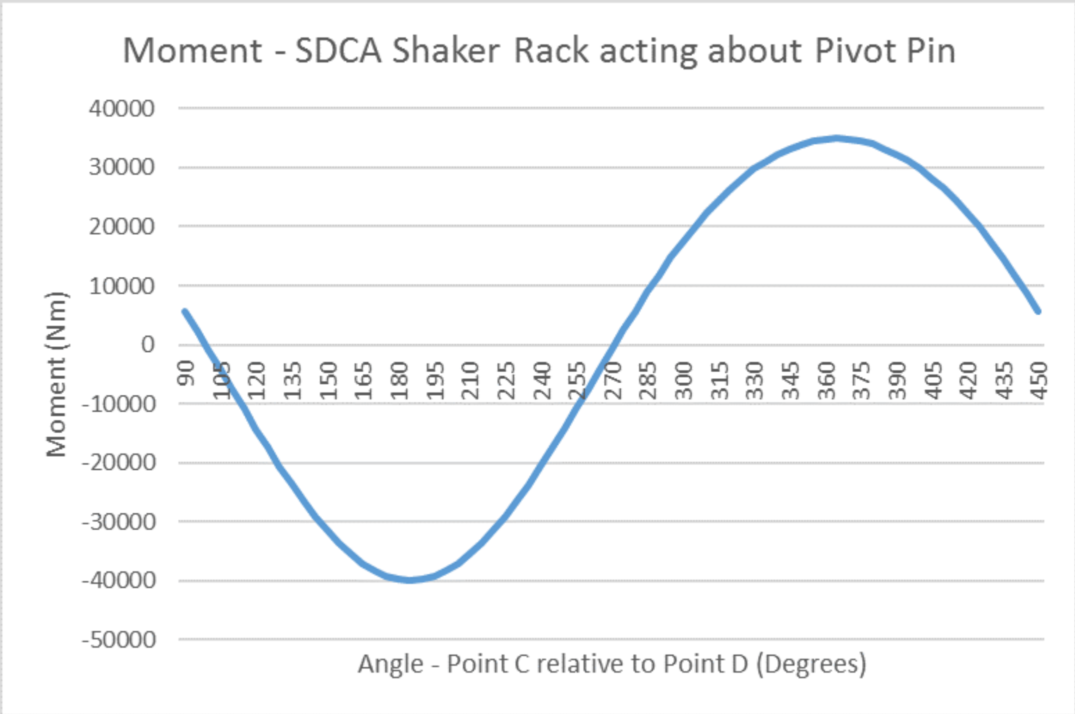

Figure 4-6: Graph of SDCA Shaker Rack acting about Pivot Pin

With reference to the moment calculation tables detailed in Appendix F and the above graph, the maximum positive and negative moments generated at the base of the SDCA occur as follows:

- $M_{10} = 34{,}797\ Nm$ – Angle of Point C relative to Point D at 10°
- $M_{185} = -39{,}871\ Nm$ – Angle of Point C relative to Point D at 185°

4.1.5. Stress Calculations

The stress experienced throughout the SDCA can be derived using the Bending Moment formula:

$$\sigma = \frac{My}{I}$$

Where;

- M – The moment with respect to time (Nm)
- y – Distance from the neutral axis (m)
- I – Second moment of Area of the SHS (m^4)

The cross-sectional area of the SHS is calculated based on Figure 4-7:

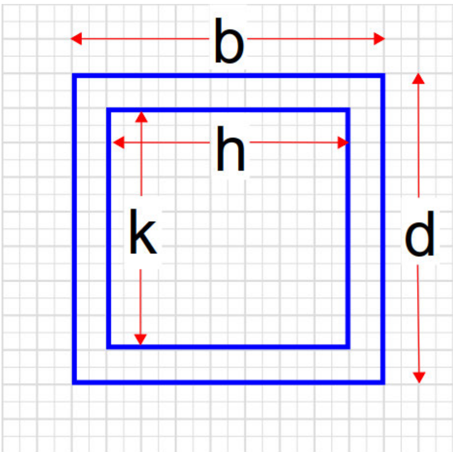

Figure 4-7: SHS Second Moment of Area (I)

With reference to the following formula:

$$I = \frac{bd^3 - hk^3}{12}$$

Based on the use of 150mm SHS, with a 10mm wall thickness, the second moment of area is:

$$I = \frac{\left(0.15\ x\ (0.15^3)\right) - \left(0.13\ x\ (0.13^3)\right)}{12} = 0.0000184\ m^4$$

The primary region of failure within the SDCA is located on the underside of the pivot pin, adjacent to the following stress raisers, identified in Figure 3-1:

- Pivot Pin Penetration
- Pivot Pin Boss
- Fillet weld

A detailed analysis of the impact of the individual stress raisers is beyond the scope of this paper, however as estimated data of the current life of SDCA's is known, the impact of the stress raisers with reference to the stress experienced on the underside of the pivot pin can be estimated.

Based on the stress calculations above, the stresses experienced below the pivot pin at the maximum moment 39,871 Nm, are detailed in Table 4-4:

Table 4-4: Bending Stress relative to Neutral Axis

Distance from Neutral Axis – y (m)	Stress (MPa)
0.015	33
0.025	54
0.035	76
0.045	98
0.055	119
0.065	141
0.075	163

4.2.THEORECTICAL FATIGUE LIFE CALCULATIONS

With reference to Juvinall and Marshek's Fundamentals of Machine Design (2012), the following sub-chapter provides an analysis of the SDCA shaft and boss assembly, for the purpose of identifying the impact of stress concentrations and estimate the fatigue life under the existing operating conditions.

The fundamental concepts associated with fatigue failure, as described by Juvinall and Marshek include:

1. Failure is as a result of repeated plastic deformation
2. Typically occurs after thousands / millions of cycles of microscopic level yielding
3. When analyzing a component, focus should be on stress concentrations where highly localized plastic yielding can be observed
4. If the local yielding is sufficiently minute, the material may strain-strengthen, causing the yielding to cease
5. The initial fatigue crack usually results in an increase in local stress concentration

4.2.1. SDCA Operating Conditions

Figure 4-8 shows the SDCA locations, as noted by the red arrows, where the OEM's proprietary design typically experienced failure. The blue arrows denote the reversed bending experienced due to loading on the connection rod (left) and connection strap (right), whilst the SDCA is constrained from translation at the pivot pin, denoted by the green arrow.

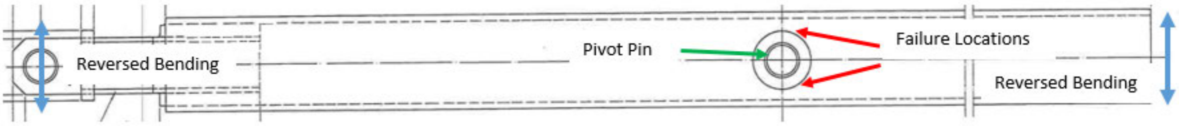

Figure 4-8: Primary SDCA Failure Location (Front View)

When designing with ferrous metal, such as with carbon and mild steel, Juvinall and Marshek advise that it is customary to design with the assumption that the material must not be stressed above an endurance limit where life of greater than 10^6 cycles is required. With reference to the cycle data in sections 2.3.3 and 4.1.1, the total cycles per annum for each SDCA is as follows:

$$n_{annual\ shaking\ cycles} \times n_{oscillations\ per\ cycle} = 1{,}971\ x\ 48 = 94{,}608\ per\ annum$$

The SDCA is required to operate for 94,608 cycles per annum, therefore the 10^6 cycle duration is achieved in just over 10 years.

$$\frac{Endurance\ Limit\ Cycles}{Cycles\ per\ annum} = \frac{1{,}000{,}000}{94{,}608} = 10.6\ years$$

The design life of the fabric filter is not detailed in the operations and maintenance manual, therefore assumptions are required to determine the design objectives. Information provided by maintenance personal at MPPS have advised that the current life of the proprietary SDCA is approximately 5 years, however there is no data available verifying this approximation. For the purpose of this analysis, it is assumed that 5 years is the average life.

To minimize operational disruption and maintenance expenditure, the objective of any modified design is to achieve a performance life that coincides with planned plant outages, which are performed on each unit every 4 years.

4.2.2. SDCA Endurance Limit Calculations

The proprietary design utilises Grade 250 structural steel with a minimum Ultimate Tensile Strength of 350 MPa and Yield Strength of 250 MPa. Therefore:

$$S_u = 350\ MPa$$

$$S_y = 250\ MPa$$

To determine the strength factor (S_n) associated with Grade 250 structural steel, the endurance limit (10^6) calculation for bending loads is applied, where:

$$S_n = S'_n C_L C_G C_S C_T C_R$$

With reference to Juvinall and Marshek's *Design of Machine Elements*, *Chapter 8*, the following calculations for bending are derived to determine the endurance limit.

- R.R. Moore Endurance Limit:

$$S'_n = 0.5 S_u = (0.5)(350\ MPa) = 175MPa$$

- Load Factor (C_L) for bending loads:

$$C_L = 1.0$$

- Gradient Factor (C_G) for 150mm SHS:

$$C_G = 0.7$$

- Surface Factor (C_S) for hot rolled structural steel, where 350 MPa converts to ~50ksi:

$$C_S = 0.75$$

- Temperature Factor (C_T), where operation is exposed to a maximum of 120°C or 248°F:

$$C_T = 1.0$$

- Reliability Factor (C_R), where a standard deviation of 8% of the nominal endurance limit is used, therefore a 99% factor is applied :

$$C_R = 0.814$$

Under these conditions, a generalised endurance limit (10^6) for 250 Grade structural steel is:

$$S_n = (175MPa)(1.0)(0.7)(0.75)(1.0)(0.814) = 75MPa$$

The corresponding 10^3 cycle strength is:

$$S_f = 0.9S_uC_T = (0.9)(175MPa)(1.0) = 157.5MPa$$

Based on the above calculations, the Sn Curve shown in Figure 4-9 can be obtained, which shows the estimated fatigue life for the SDCA, where infinite life can be achieved with a design that has a peak alternating stress of less than 75 MPa.

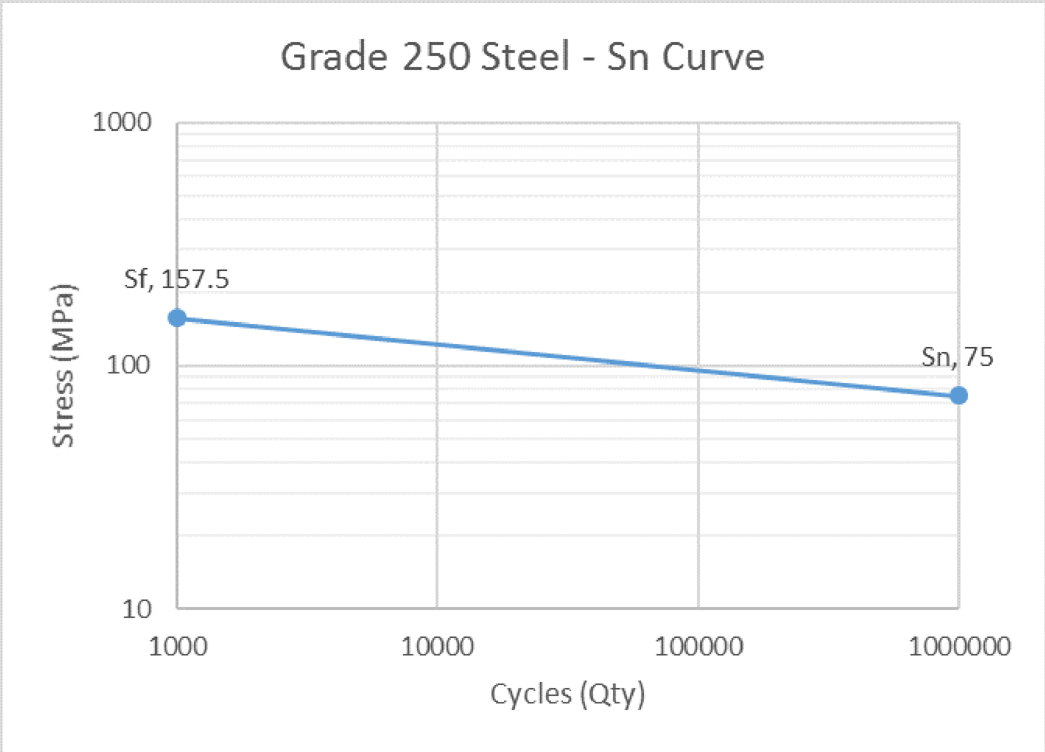

Figure 4-9: Grade 250 Steel Sn Curve

Referencing the estimated 5 year average SDCA life and the number of cycles experienced by an SDCA per annum, the current estimated SDCA life is as follows:

$$n_{Years} \times n_{annual\ shaking\ cycles} \times n_{oscillations\ per\ cycle} = 5 \times 1{,}971 \times 48 = 473{,}040$$

Therefore, the current estimated life of an SDCA is 473,040 cycles. When applying this value to the above Sn Curve for Grade 250 Steel, the peak alternating stress value for 473,040 cycles is ~90 MPa.

Given the values obtained from the Sn Curve are general estimates, as noted by Juvinall and Marshek, in conjunction with the unavailability of theoretical data available to analyse the stress concentrations in the SDCA's, this conclusion can only be for information only, rather than the basis of any further analysis of existing or proposed designs.

4.3. FEM ANALYSIS – DESIGN ITERATIONS

With reference to Chapter 3.1.2 and drawing 7001-0706, an analysis against the current design in use (Design iteration 2), as well as the other design iterations 3 to 6, is undertaken to verify the investigation results against modelling in Creo.

Utilising the calculated maximum bending moment of 163 MPa within the currently utilised design (Design Iteration 2) as the benchmark for simulation in Creo, the initial models in this section are based on the following constraint / load application:

- Pivot pin bush is constrained against translation, however free to rotate in all directions
- Top of SDCA is constrained from translation
- Loading applied to base of SDCA = 15,000N

Following is a summary of the static analysis results and maximum stress locations for design iterations 1 to 6. Additional detail is contained in Appendix E.

4.3.1. Design Iteration 1 (DI1): Modified SHS – 150mm x 150mm x 9mm

DI1 receives a maximum stress located at the interface of the weld and the SHS on the far side bush on the SHS section of the SDCA. This location replicates the region where the failed examples showed evidence of strain hardening and crack formation.

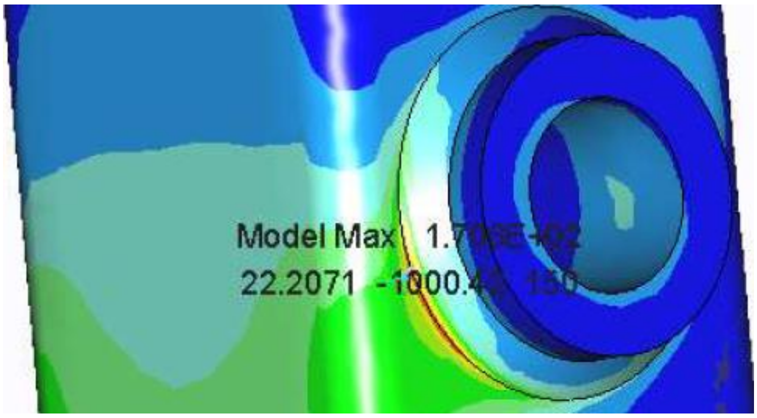

Figure 4-10: 150mm x 150mm x 9mm SHS – Maximum Stress

As noted in Figure 4-10, maximum stress is 170MPa, with a reduction in stresses extending from the pivot pin. There is also an area of stress concentration at the base of the shaker drive mechanism, the extent of this concentration is heavily reliant on the welding configuration in this region and smoothing of edges.

4.3.2. Design Iteration 2 (DI2): Modified SHS – 150mm x 150mm x 10mm

DI2 is the current SDCA design being utilised and will for the benchmark for the proposed solution analysis. Maximum stress occurs in the same region as DI1, however the stress value is reduced by 7MPa as shown in the below image.

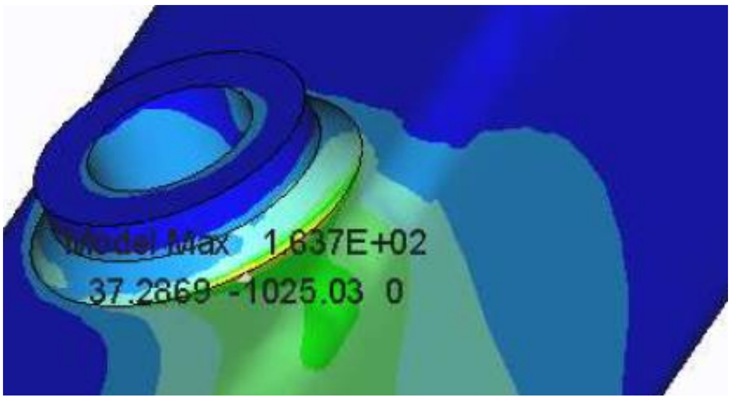

Figure 4-11: 150mm x 150mm x 10mm SHS – Maximum Stress

The maximum stress is also more consistent with the adjacent SHS, which indicates that the stress raiser has been partially nullified by the increase in wall thickness.

4.3.3. Design Iteration 3 (DI3): 400mm Plate Sections

The addition of the 2 off 400mm plates on the SHS across the bush centerline have reduced the stress around the bush connection, however the stress concentration has been relocated to the underside weld of the 400mm plate. Figure 4-12 shows an enlarged view of the stress concentration along the underside of the 400mm plate weld.

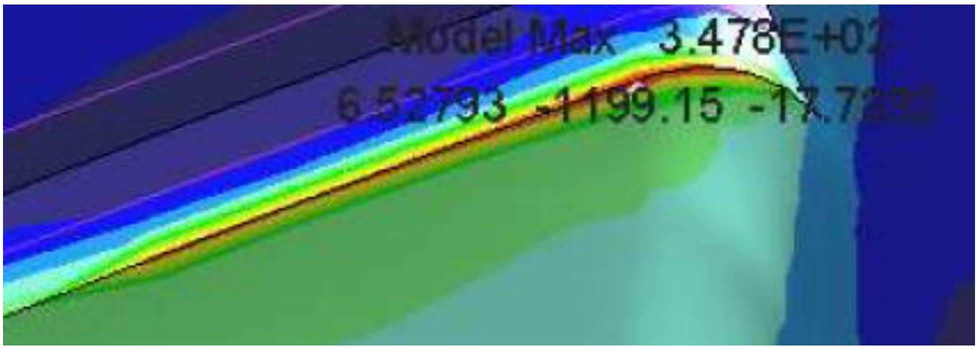

Figure 4-12: 400mm Plate Sections – Maximum Stress

This has caused an increase in the maximum stress, subsequently based on this analysis failure could be expected to occur sooner that DI1 and DI2.

4.3.4. Design Iteration 4 (DI4): Full Plate Sections

DI4 has resulted in a reduction in maximum stress, however it has been transferred to the 60mm x 90mm shaker drive mechanism at the top of the SDCA as shown in Figure 4-13. This correlates with the location where this design was proven to fail by shear stresses in operation.

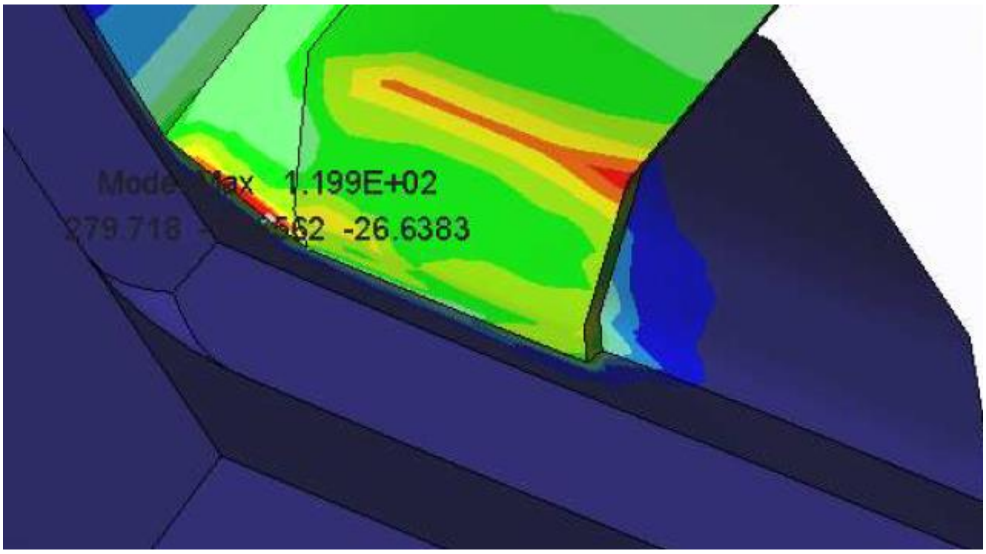

Figure 4-13: Full Plate Sections Welded to SHS – Maximum Stress

This design failed shortly after installation, subsequently the remaining SDCA's fabricated with this design were removed from service. As this design attempted to remove the stress from the SHS, which resulted in a much shorter life, any proposed designs should seek to maintain the maximum stresses throughout the SHS, however identify a way to reduce their impact to stress raisers.

It should also be noted that an accurate simulated assessment of the shaker drive mechanism shown is not possible, due to the large number of stress concentrations in this region, which include various plates, chamfers and welds, each containing minor variations in fabrication. A design that limits the maximum stresses from impacting the shaker drive mechanism region, noted in Figure 4-19, is likely to achieve a greater consistency of performance.

4.3.5. Design Iteration 5 (DI5): Additional Weld around Boss

For the purpose of modelling design iteration 5, a 14mm weld has been introduced, increasing from the 10mm weld, this is indicative of the weld size / additional weld run that was applied in this iteration.

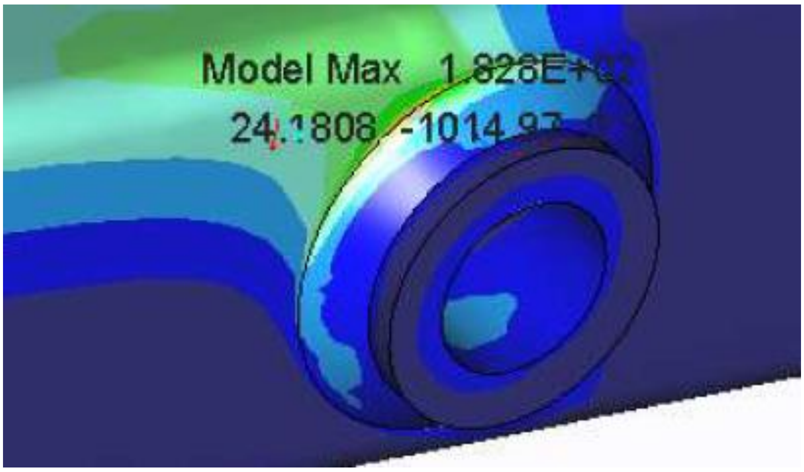

Figure 4-14: Increase in Weld Thickness around Boss – Maximum Stress

As shown in Figure 4-14, the additional weld has made an increase of maximum stress by 19 MPa. The maximum stress location remains at the interface of the weld and the SHS.

4.3.6. Design Iteration Summary

As detailed in the following summary, the evidence derived from the FEM simulation verifies that the design iterations either increased the stresses experienced in the SDCA, or they relocated the maximum stress to the shaker drive mechanism region of the SDCA, which has a greater concentration of stress raisers and likely variances in fabrication.

The only value which showed an improvement in the maximum stress experienced is Design Iteration 4 (DI4), however this is only due to the principle stress being removed from the SHS section of the SDCA, to the shaker drive mechanism (60 x 90mm section) above SHS, which was found to shear shortly after installation.

Table 4-5: Design Iteration Results

Ref	Description	Max Stress (MPa)	Stress Location	Max Stress Variance (MPa)
DI1	150mm x 150mm x 9mm SHS	170	Far side Bush	+7
DI2	150mm x 150mm x 10mm SHS	163	Far side Bush	0
DI3	400mm x 10mm plates added	348	400mm Plate	+185
DI4	Full length plates added	119	Shaker Drive	-44
DI5	Additional weld at Boss	182	Far side Bush	+19

4.4. FEM ANALYSIS - PROPOSED DESIGNS

Following the proposed solutions identified in Chapter 3.4, the following details the calculations and analysis associated with each proposal. In all instances, modelling has been based on the use of 150mm x 150mm x 10mm grade 250 steel.

4.4.1. Proposed Solution 1 (PS1) – Tapered Plates on Bush Side

Preliminary analysis conducted with a 10mm taper plate arrangement that extends to a point 900mm either side of the boss, to a maximum width of 110mm at the centre of boss. This taper is welded on all edges with 10mm weld, with the boss weld then placed on the top of the taper.

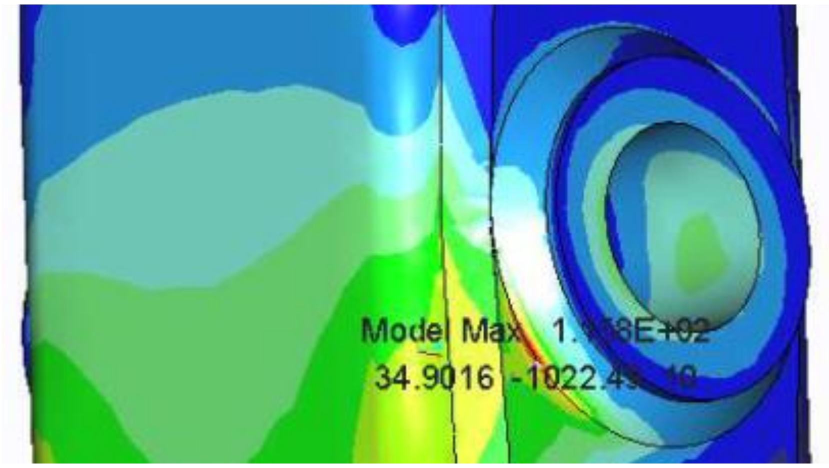

Figure 4-15: Tapered Plates on Both Side – Maximum Stress

Initial analysis has shown a reduction in maximum stress to 116MPa, which is occurring at the interface between the weld and the taper plate as shown in Figure 4-15. However further simulation of the dimensions could be undertaken in conjunction with trialing a model of this assembly to ascertain further improvements to this design.

4.4.2. Proposed Solution 2 (PS2) – Tapered Plates on Non Bush Side

As with PS1, the intent of this design is to relocate stresses that occur around the boss, to the remainder of the SHS to reduce the stress concentration in this region. This shows a reduction in maximum stress to 115MPa, which is located at the shaker mechanism drive as shown in Figure 4-16. This is a similar result to DI4 where full plates were welded to either side and would potentially result in a failure at the shaker mechanism.

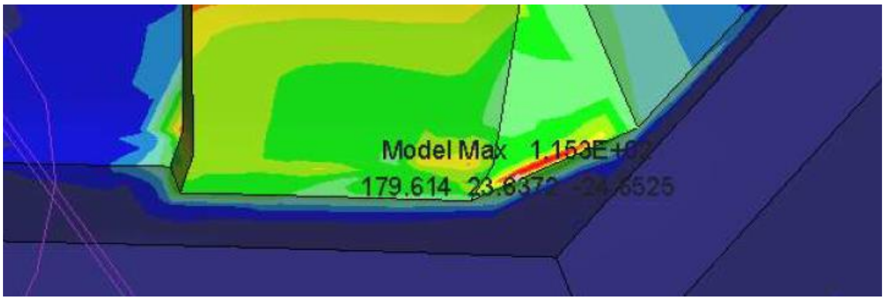

Figure 4-16: Tapered Plates on Non Boss Side – Maximum Stress

Further dimensional analysis could be undertaken to determine the optimal taper plate design in this configuration, whereby the stress is reduced around the pivot pin, however ensuring that excessive stress is not transferred to the stress raiser located at the connection between the shaker mechanism and the SHS.

However, as noted in Chapter 4.3.4, the large concentration of stress raisers and their associated variations from the fabrication process, suggest that a maximum stress generated around the shaker drive mechanism should be avoided.

4.4.3. Proposed Solution 3 (PS3) – Reduce Wall Thickness of Boss OD

The preliminary model of PS3 is based on a reduction of the boss OD to 75mm, from the 90mm specified.

This has resulted in a significant increase in maximum stress to 197MPa, which is based on the interface of the inside wall of the SHS and the boss as shown in the sectional view shown in Figure 4-17. A reduction in wall thickness of the boss appears unsuitable based on this analysis, however there is an opportunity for further analysis to verify that the 90mm OD is the optimum boss thickness.

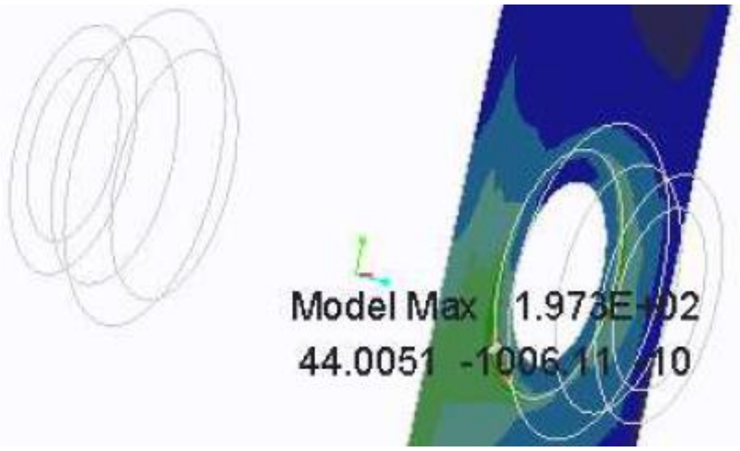

Figure 4-17: Reduce Wall Thickness of Boss OD – Maximum Stress

4.4.4. Proposed Solution 4 (PS4) – Butt Weld Boss to SHS Structure

PS4 involves the reduction of the boss so that it is flush with the SHS, with the join used a butt weld between the face of the SHS and the outside of the boss. The intent is to remove the stress concentration generated by the boss and 10mm fillet weld.

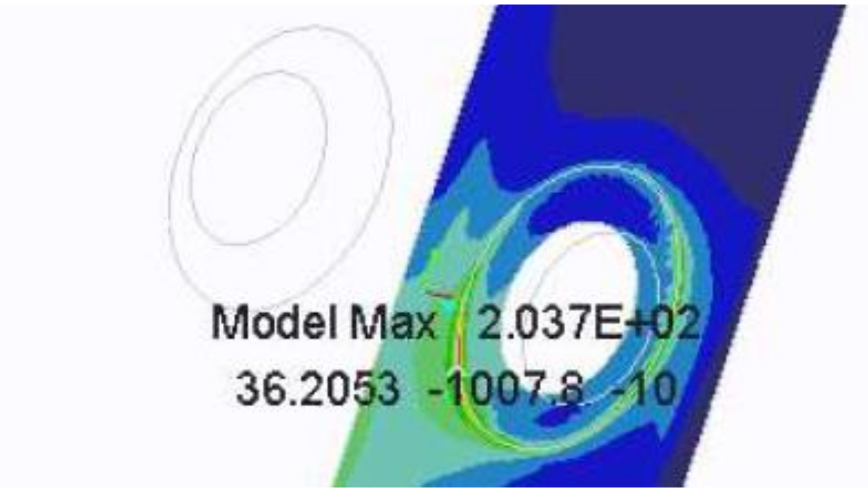

Figure 4-18: Butt Weld Boss to SHS Structure

As detailed in Figure 4-18, the analysis result shows a 40MPa increase relative to the current design, with the maximum stress located on the internal interface between the SHS and boss.

4.4.5. Proposed Design Summary

In all instances of the design iteration models, the static analysis results correlate with the fracture locations identified through inspections of the failed SDCA's.

Following is a summary of results of the static analysis of the current design compared to the proposed designs undertaken in Creo. Note that Design Iteration 2 (DI2) is currently in use, therefore it is the benchmark for maximum stress variance calculations.

Table 4-6: Proposed Design FEM Analysis Results

Ref	Description	Max Stress (MPa)	Stress Location	Max Stress Variance (MPa)
DI2	Current design 150 x 150 x 10	163	Far side Bush	0
PS1	Taper Added – Boss Side	116	Far side Bush	-47
PS2	Taper Added – Non Boss Side	115	Shaker Drive	-48
PS3	Reduction in Boss wall thickness	197	Far side Bush	+34
PS4	Butt weld boss to SHS	203	SHS Plate	+40

As referenced in the above table, in some instances the model has identified that the maximum stress location is located at the 'Far Side Bush', which is based at the base of the weld in the region between the bush and the SHS. This reference to far side bush is relative to the side of the SHS where the shaker drive mechanism is connected to the SDCA, this is further explained in Figure 4-19.

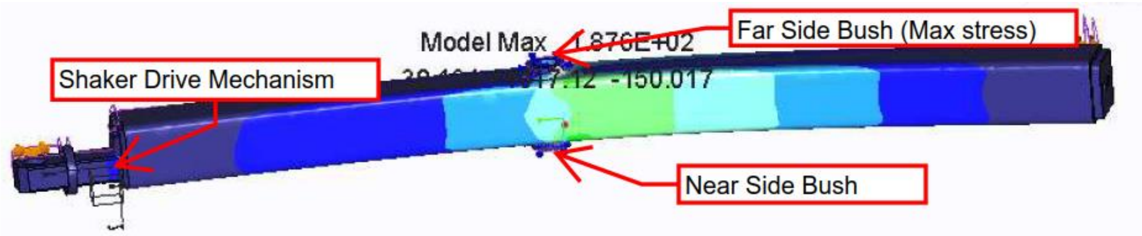

Figure 4-19: Maximum Stress Located at Far Side Bush

4.5.PROPOSED DESIGN SOLUTION

The proposed design study has shown that the likely most effective design is the use of taper plates on the boss sides of the SDCA. The primary reasons for selecting this design are as follows:

- ~30% reduction in maximum stress experienced, with the maximum stress reducing from 163MPa to 116MPa
- The maximum stress is impacting near the boss, however it is in a region where there is minimal variance in fabrication, therefore consistency in fabrication and performance should be achieved

CHAPTER 5: CONSEQUENCES AND BENEFITS

As noted in the section 3.1.5, the major limitation with this paper is the lack of historical record keeping, which results in the use of assumptions throughout the review and has restricted the identification of tangible benefits associated with any design change.

Separate to the proposed design modification, there are recommendations regarding the quality assurance and maintenance processes utilised, which are detailed as follows.

5.1 QUALITY ASSURANCE

Through inspection of the failed SDCA's, it was identified that there were potentially some quality control issues as detailed in sections 3.1.1 and 3.1.4, such as evidence of lack of weld penetration.

Further, one of the design iterations detailed in section 3.1.2, involved additional weld runs being applied to the original weld around the boss as a means of reinforcement, however without verifying the integrity of the initial weld process to provide a performance base, it is not possible to gauge the effectiveness of including additional welds to the design.

It is therefore recommended that the fabrication process be supported with a quality assurance procedure that ensures a consistent product is being produced for each replacement. This could include the following additions to the existing process:

- Design drawing: An updated drawing created to detail the current design
- Weld procedure: A documented procedure detailing the weld requirements
- Welder qualification: A qualification and testing process for all welders

- Inspection / Testing: Non-destructive testing on a percentage of SDCA’s to verify compliance with design
- Material certificates: Verification of the source of each steel component supplied
- Fabrication identification: Each SDCA provided a unique number used for tracking through fabrication, installation and operation

Whilst the inclusion of these processes would incur additional time and costs, particularly as the welding is currently performed off site, it will provide a process for ensuring the SDCA’s are provided in accordance with the design. Further, it will allow for additional supporting evidence to understand the contributing factors to future failures and allow the basis for rectifying these factors.

5.2 MAINTENANCE

As identified in previous chapters, there is currently no method for recording the life of SDCA’s, so whilst there is an average estimated life of 5 years, there is no way of verifying if this is a correct assumption. Further, there is no method for tracking if there are variations in the performance of SDCA’s specific to certain locations within each cell, which could potentially be attributed to:

- Operational performance of ancillary plant, such as misalignment of motors and shafts increasing the loading on SDCA’s
- Loading variances due to volume of dust captured on fabric filter bags, increasing the mass moment of inertia loading on SDCA’s based on their location in the cell

By understanding these variations, it may allow more targeted approach to maintenance, such as:

- Performing maintenance on the ancillary plant as opposed to continuing to replace SDCA's that are failing more frequently, or;
- Identifying locations within the SDCA where greater volumes of dust are being captured, such as locations closer to the inlet from the boiler.

In addition to this, it can also provide a tracking mechanism for identifying if there are failures specific to a welder, steel batch or steel supplier.

The recommended approach, with reference to Figure 2-10, is to create spreadsheet where each cell is numbered 1 through to 80, in conjunction with the numbering of each SDCA within that cell. For example, "SDCA-78-5", would relate to the SDCA 5 located within cell 78. Then for each SDCA location, track the installation date, replacement date and fabrication identification provided in the quality assurance process.

5.3 COST ANALYSIS

As proposed solution 1 appears the most effective solution assessed, the cost benefit of this design will be associated with a reduction in the frequency of undertaking the maintenance activities, however would be partially offset by the increase in fabrication and material costs.

Given the assumptions required to analyse the stress concentration factors impacting the boss region of the SDCA, the cost analysis will assume an increase in life by either 50% or 100%, in conjunction with an allowance for additional material and fabrication costs associated with proposed solution 1.

The following calculations are derived with reference to the estimated maintenance expenditure calculated in Chapter 3.2.2.

Estimated 50% Increase in life

The current estimated life of an SDCA is 5 years, making the assumption that the design increases the life by 50%, this would result in SDCA's requiring replacement every 7.5 years. With 100 SDCA's currently being replaced per annum, as noted in Chapter 3.2.2, this would reduce to approximately 67 SDCA's replaced per annum.

Estimated 100% Increase in life

Under this scenario, SDCA's would only require replacement an average of every 10 years, therefore the annual replacement quantity would be halved to 50.

Fabrication Allowance

The existing fabrication costs are $1,000 per SDCA, however with proposed solution 1, there is an additional ~10 metres of welding and associated material preparation. It is assumed that this would increase the fabrication time by approximately 8 man hours per SDCA. Assuming a workshop labour rate of $60 per hour, this would increase the fabrication costs by about 50% to $1,500 per SDCA.

Cost Analysis Summary

A summary of these scenarios is provided in the following Table 5-1:

Table 5-1: SDCA Replacement Cost Analysis Summary

Cost Centre	**Current Design**	**50% Life Increase**	**100% Life Increase**
Fabrication	$1,000	$1,500	$1,500
Installation	$1,160	$1,160	$1,160
Annual Quantity	100	67	50
Annual Cost	$216,000	$178,220	$133,000

The proposed design cost is $1,500 for fabrication and $1,160 for installation, totalling $2,660, is the estimated cost regardless of the increased life of the SDCA. However, by comparing this cost to the current annual cost, we can ascertain the minimum life increase required for this to be a feasible solution:

$$Proposed \div Existing = \$2{,}660 \div \$2{,}160 = \sim 125\%$$

Therefore, for this design to be beneficial on a purely cost basis, the minimum life increase required is 25%.

The actual cost benefit will be difficult to gauge accurately without trialling the proposed SDCA solutions and tracking their performance, however this provides a performance benchmark for assessing whether the design should be changed once a trial has been completed.

5.4 FURTHER WORKS

As there appears to be some scope for an increase in life associated with the introduction of the taper plates identified in proposed solution 1, the next step would be to finalise an optimum dimensional configuration for fabrication and trial.

In conjunction with this trial, the introduction of a quality assurance process that monitors the performance of the SDCA, so that any further design iterations can be introduced and monitored. This would provide the basis for continuous improvement in the design.

Once the design performance has been quantified, there is the potential to undertake a similar analysis at other sites that are experiencing similar failure issues.

Separately, there is also the opportunity to trial a completely modified design, utilising different structural components and materials, such as grade 450 steel. However, with any new design concept, the quality assurance process needs to exist to effectively monitor performance.

CHAPTER 6: CONCLUSION

There appears to be much empirical data on the functionality of fabric filters, with regards to the efficient removal of particulate matter from the fabric and the subsequent performance of varying designs. However, I was unable to identify any record of analysis of the fatigue life of SDCA infrastructure, which in the case of power stations and other manufacturing processes in Australia, is often plant that has been in service for several decades.

As is the case with the MPPS fabric filter, this plant is based on a design was likely developed utilising engineering principles for stress concentration and static loading, without the advantage of current modelling techniques utilising dynamic analysis and fatigue life loading.

It is difficult to establish a single root cause for the failure of the SDCA's, with many assumptions utilised throughout due to limited historical data. However, based on the known information, the following contributing factors have been identified:

- **Design:** The SDCA design contains stress raisers around the pivot pin where failure predominantly occurs at an average life of 5 years. As there is no data available from the OEM on the expected life for these components, it is not known whether this is a design flaw, or merely a maintenance requirement. Through modifications to the design, it is possible to theoretically extend the life of the SDCA's, however this increase is difficult to quantify and will only be known if the performance of new design against old design is measured.
- **Quality Assurance:** No quality assurance procedure is in place during the fabrication process, therefore it is difficult to measure the performance of the existing design when the quality of fabrication is not verified prior to being placed in service.

As noted, there are some original SDCA’s in service, which indicates the potential for anomalies in quality.

- **Maintenance:** There is no means for tracking failures based on their location within their cells. Therefore it is difficult to identify if there are factors local to each of the installation locations, such as issues with the ancillary components attached to the SDCA and/or if they are subjected to greater loading.

Should the above factors be addressed, it will be possible to establish the increased life generated by design modifications and develop further iterations to the design to maximise efficiency.

Potentially other facilities where fabric filter infrastructure is utilised, particularly that designed and installed prior to the use of 3D modelling, would benefit from the application of similar modifications to assist in the reduction of operational expenditure at a time where manufacturing outside of Australia is often deemed the more cost effective solution.

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APPENDIX A

ENG4111/4112 Research Project

Project Specification

For:	John Martin
Title:	Fabric Filter Shaker Frame Operational Analysis
Major:	Mechanical Engineering
Supervisors:	Andreas Helwig and Ray Malpress
Enrolment:	ENG4111 – EXT S1, 2017 ENG4112 – EXT S2, 2017
Project Aim:	To increase the life of the existing baghouse shaker frames utilised within industrial facilities such as power stations, without negatively impacting the operational performance of the ancillary plant.
Programme:	**Version 1, 18th March 2017**

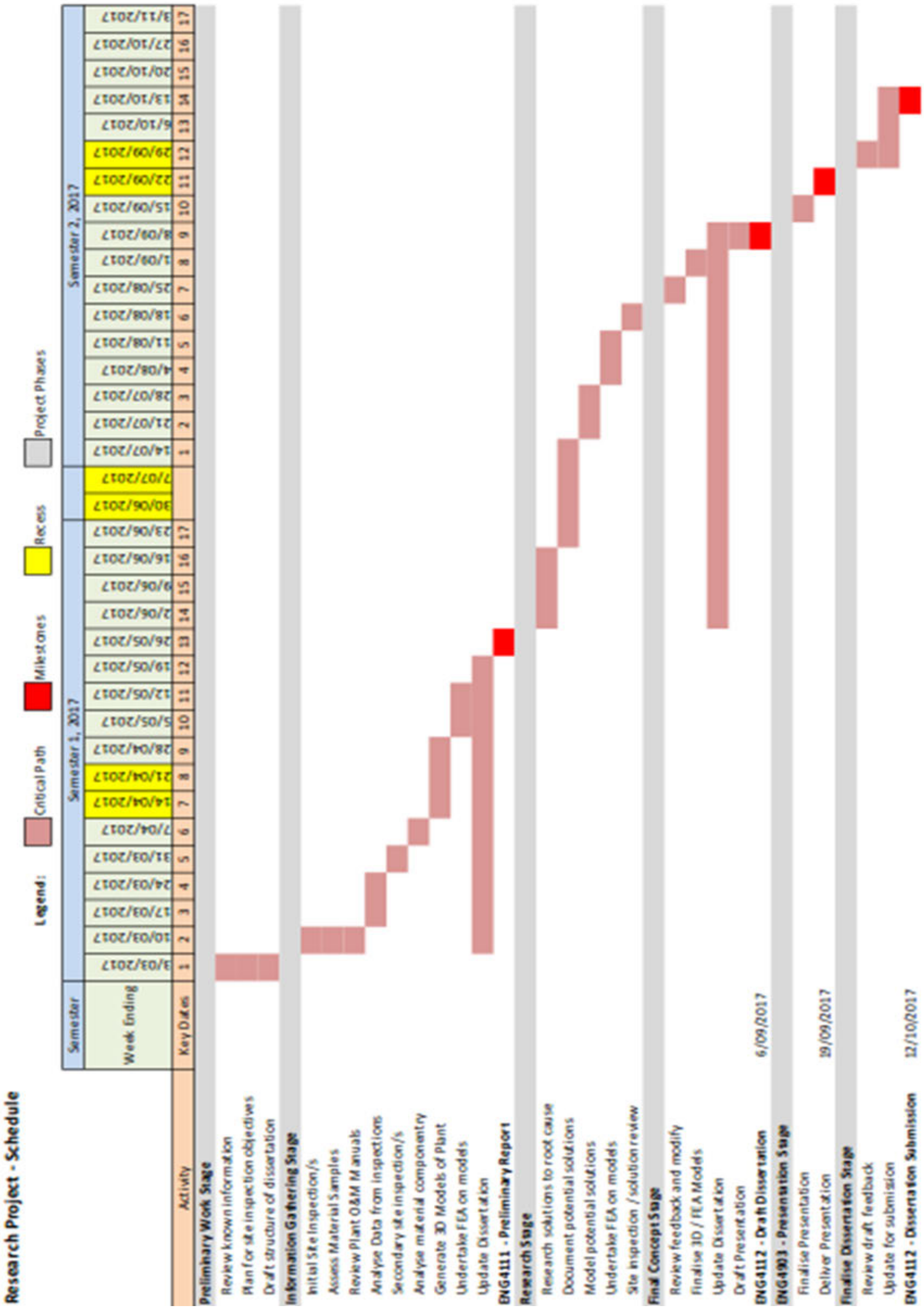
1. Assess existing shaker frame infrastructure to understand methods of failure for the proprietary design and subsequent iterations of this design
2. Research the operating environment and design constraints for this infrastructure and any proposed solutions
3. Model existing infrastructure and undertake finite element and dynamic analysis on components
4. Develop proposed solutions for mitigating these failure modes, ensuring compliance with the design constraints identified
5. Model and perform finite element and dynamic analysis of these proposed solutions to confirm a potential improvement in operational performance against the existing design
6. Undertake a cost analysis of capital and operational expenditure of the proposed design against the costs incurred with the existing infrastructure

If an alternative solution is identified, with time and resources permitting:

7. Propose the solution to the maintenance personnel / asset owner requesting permission to trial the modified design
8. If accepted, organise the fabrication and installation of a trial shaker frame

APPENDIX B

1. PROJECT SCHEDULE (GANTT CHART)



2. RISK ASSESSMENT

RISK MATRIX - ADAPTED FROM ISO 31000:2009

E - Extreme Risk - Detailed action plan required to manage risk before progressing
H - High Risk - Needs immediate senior management attention
M - Medium Risk - Specify management responsibility
L - Low Risk - Manage by routine procedures

					CONSEQUENCE				
				People	Injuries or ailments not requiring medical treatment	Minor injuries or First Aid treatment	Serious injury causing hospitilisation or multiple medical treatment cases	life threatening injury or multiple serious injuries causing hospitilisation	Death or multiple life threatening injuries
LIKELIHOOD	Probability	Historical			insignificant	Minor	Moderate	Major	Catastrophic
					1	2	3	4	5
	>1 in 10	Is expected to occur in most circumstances	5	Almost Certain	M	H	H	E	E
	1 in 10 - 100	Will probably occur	4	Likely	M	M	H	H	E
	1 in 100 - 1000	Might occur at some time in the future	3	Possible	L	M	M	H	E
	1 in 1000 - 10 000	Could occur but doubtful	2	Unlikely	L	M	M	H	H
	1 in 10 000 - 100 000	May occur but only in exceptional circumstances	1	Rare	L	L	M	M	H

Risk Assessment

Task	Hazards	Risk Rating without controls	Control/s	Risk Rating with Controls
Travelling in car to site	Crash due to: Fatigue Mechanical Issues Wildlife	E	Break every 2 hours on journey Advise contact prior to leaving of the anticipated arrival time Ensure vehicle is roadworthy Avoid driving at dawn / dusk unless absolutely necessary	L
Travelling in plane to site	General airline related hazards Strains associated with luggage	M	Follow the airline safety instructions Ensure bag weight does not exceed 23kg	L
General Site Inspection	General operational facility hazards	H	Verify appropriate PPE before attending site Undertake the appropriate inductions once at site	L
Inspecting the Ash Plant	General operational facility hazards	H	As per above Undertake the appropriate induction for the Ash Plant Develop a task specific methodology and SWMS prior to commencement	L
Undertaking activities not address in Induction / SWMS	Have not appropriately assessed hazards	H	Undertake a Take 5 Assessment. If any identified risks are greater than 'Low Risk', then develop a SWMS for review and sign off with site management	L
Research and Computer Work	Discomfort associated with ergonomics	M	Ensure suitable study furniture is used Position computer screens as eye level Take regular breaks to stretch	L

APPENDIX C

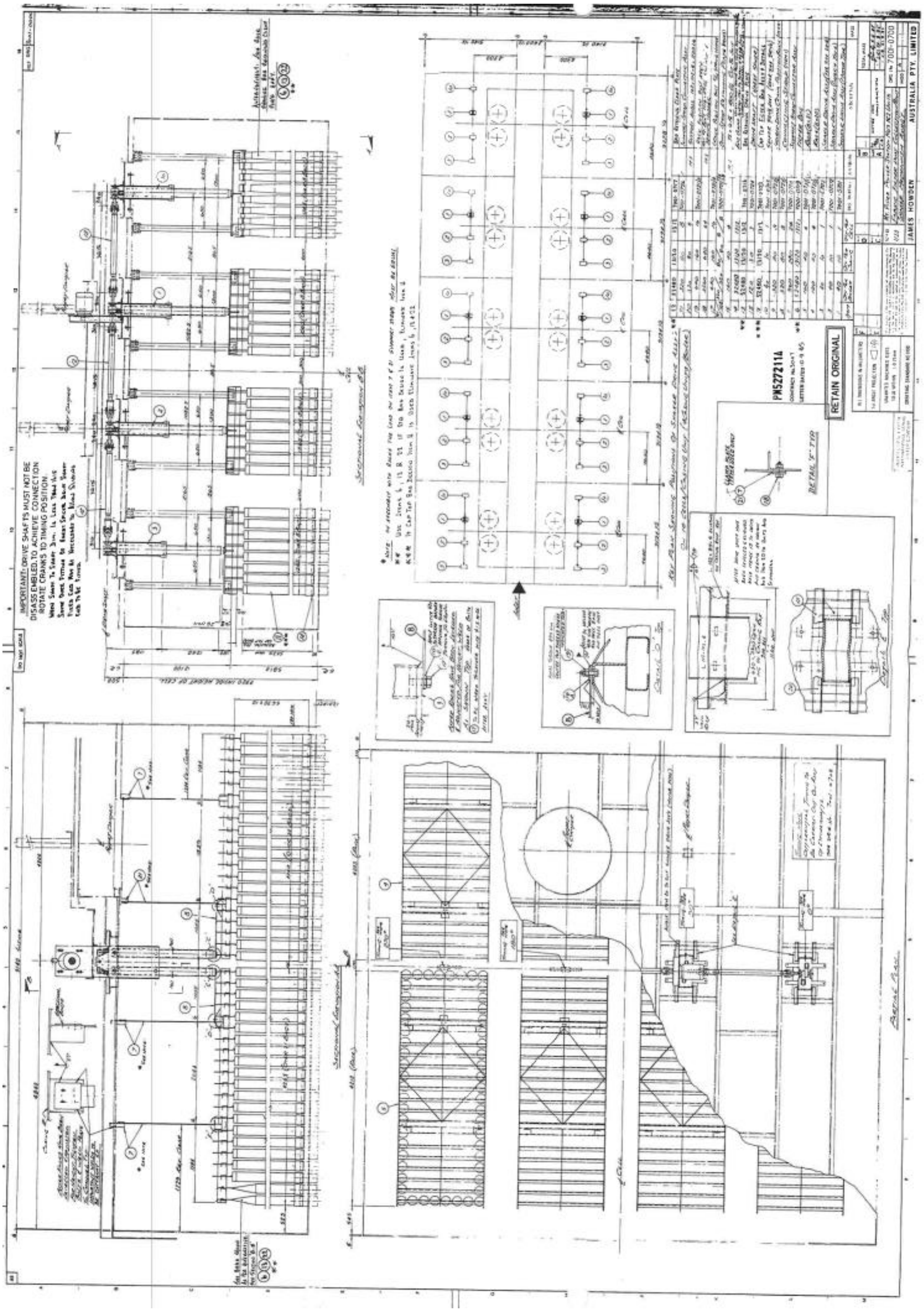
The following table details the resources sourced and utilised throughout the project to date:

Table B-1: Project Resources

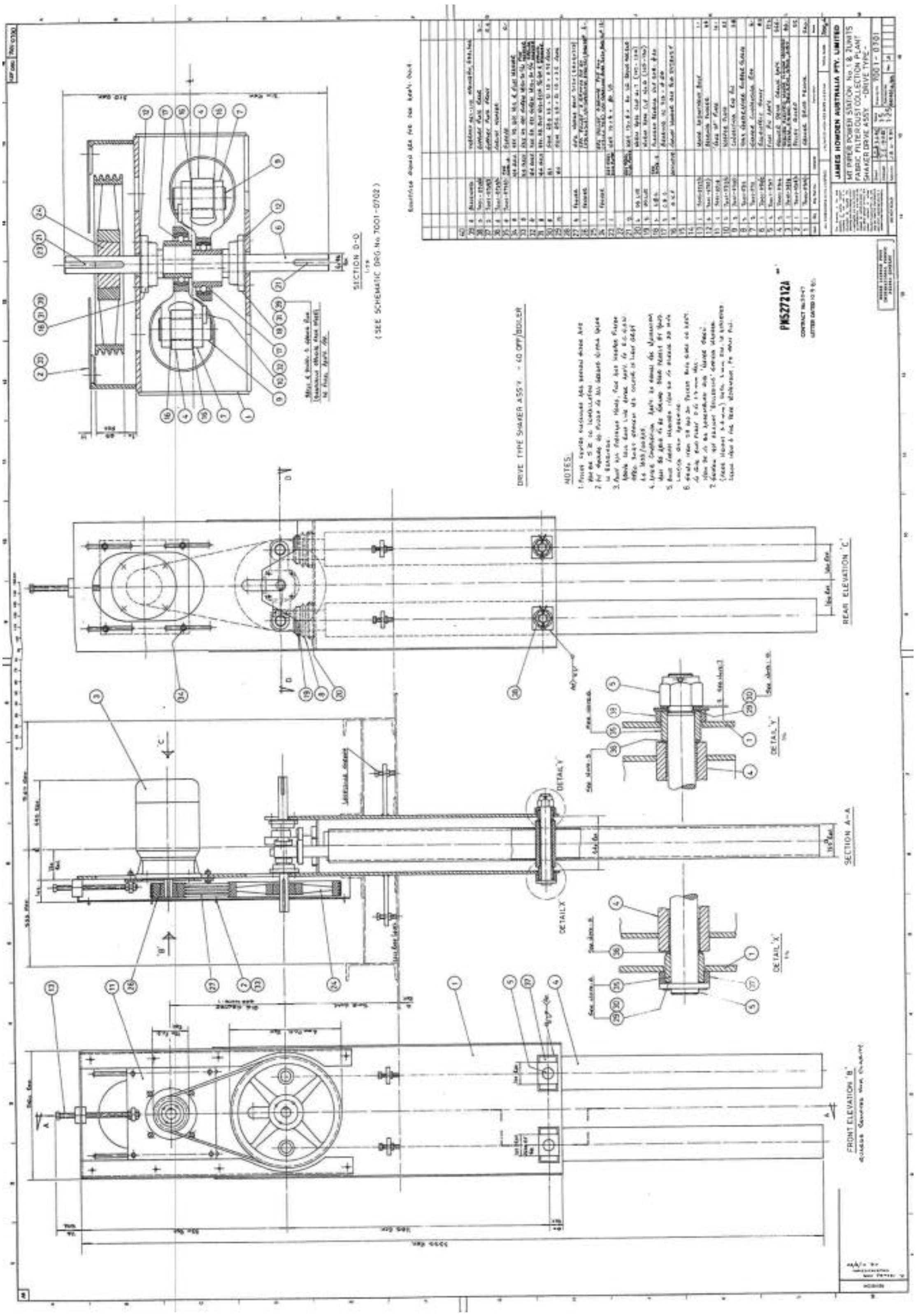
Ref.	Description	Quantity	Source	Cost
1	Camera	1	Personal Phone	$0
2	Brinnell Hardness Tester	1	Work	$0
3	Steel rule	1	Work	$0
4	Computer	1	Personal Computer	$0
5	Microsoft Excel	1	Personal Computer	$0
6	Microsoft Word	1	Personal Computer	$0
7	Microsoft Project	1	Personal Computer	$0
8	Office Supplies	1	Work	$0
9	Creo (Student)	1	Personal Computer	$0

APPENDIX D

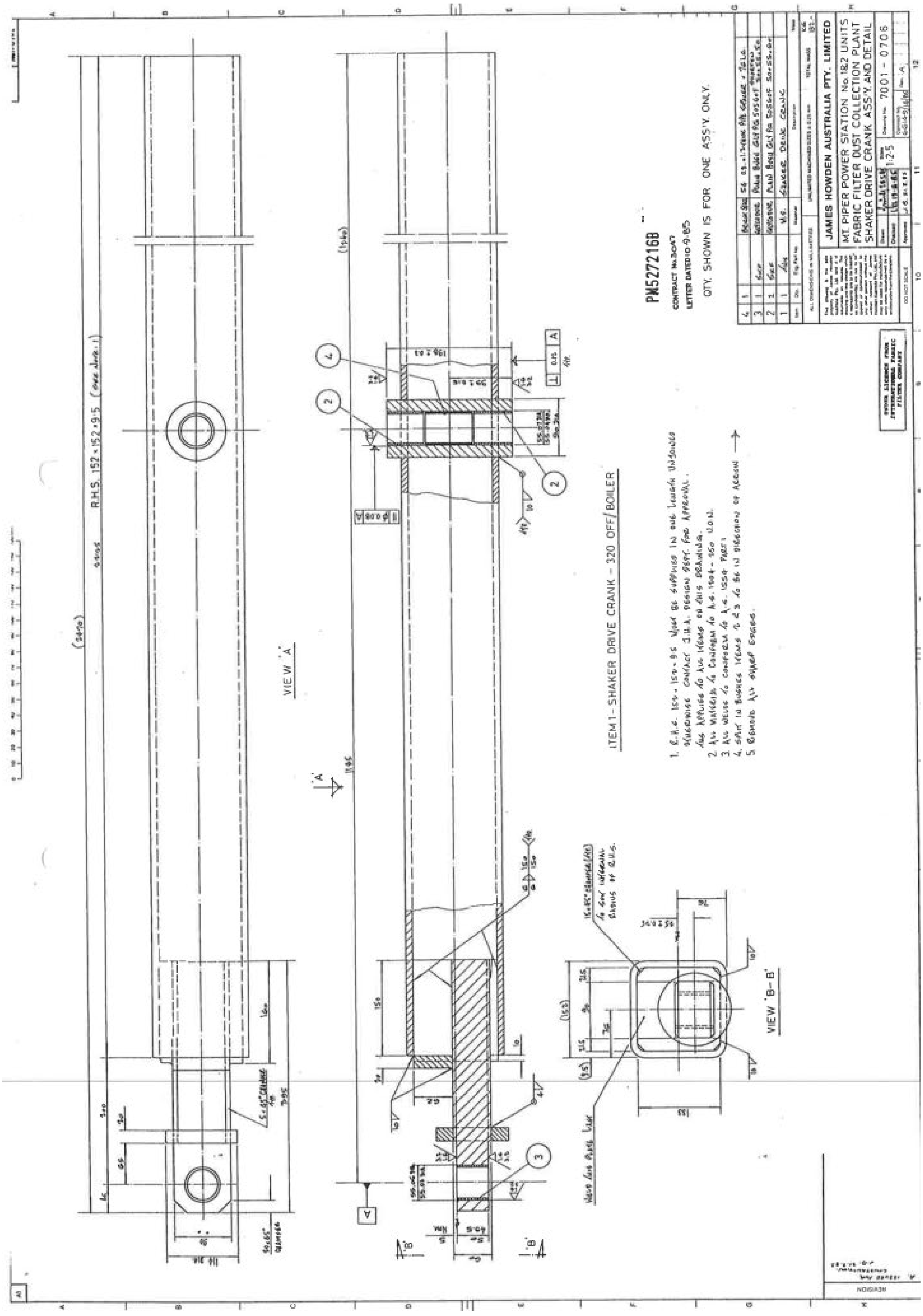
1. DRAWING 7001-0700 SHAKER MECHANISM



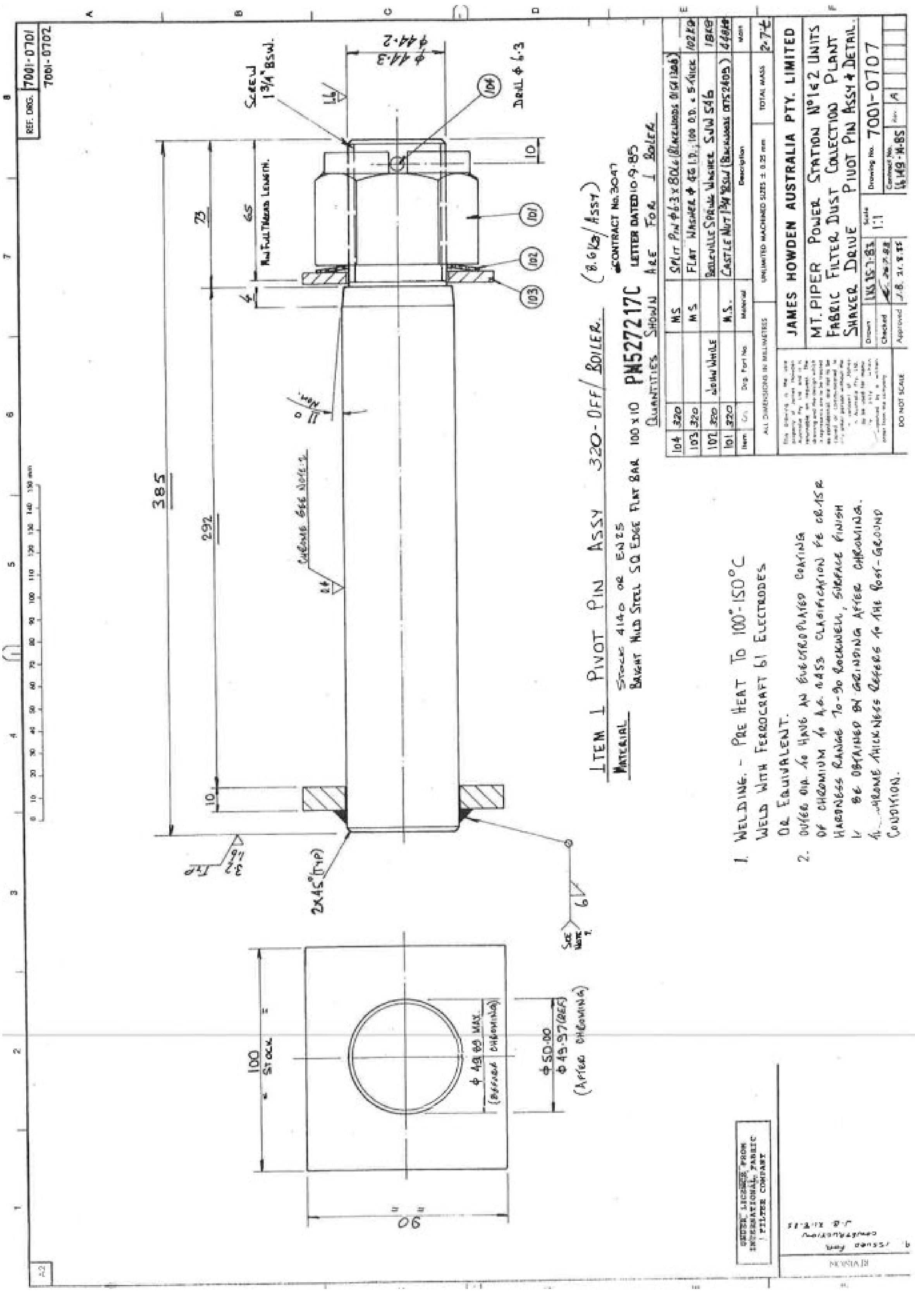
2. DRAWING 7001-0701 DRIVE ASSEMBLY



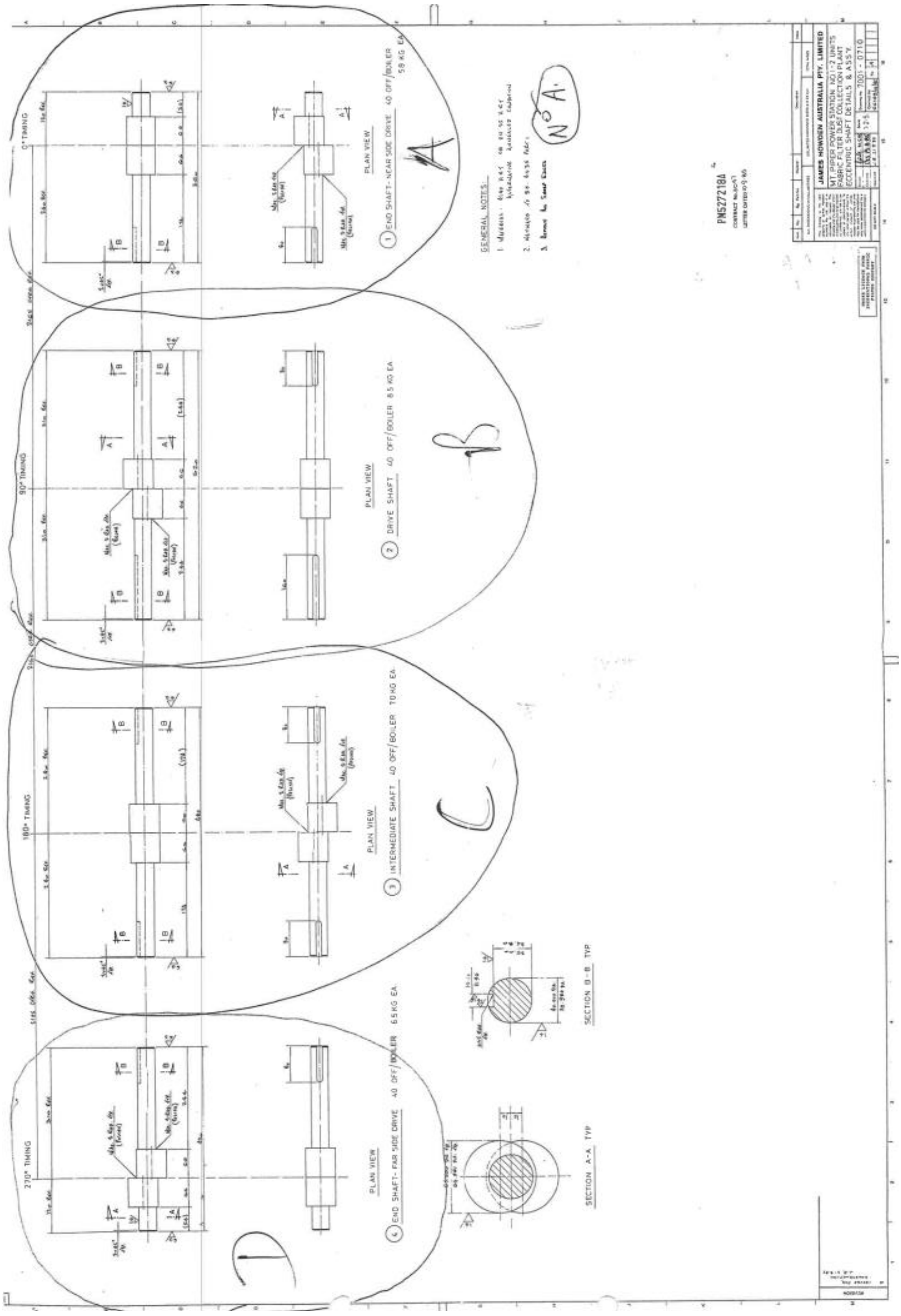
3. DRAWING 7001-0706 SHAKER ARM



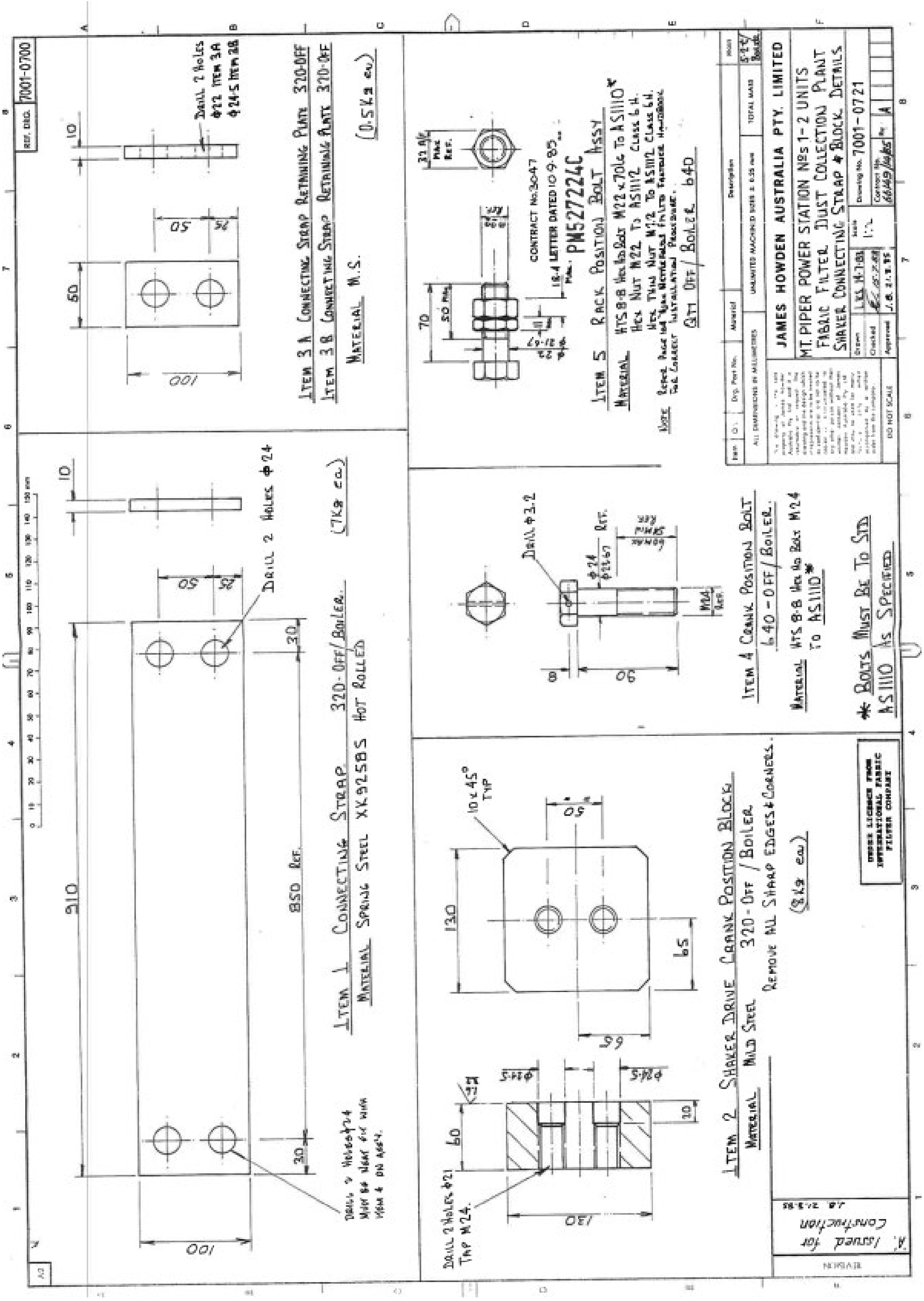
4. DRAWING 7001-0707 PIVOT PIN ASSEMBLY



5. DRAWING 7001-0710 ECCENTRIC SHAFT

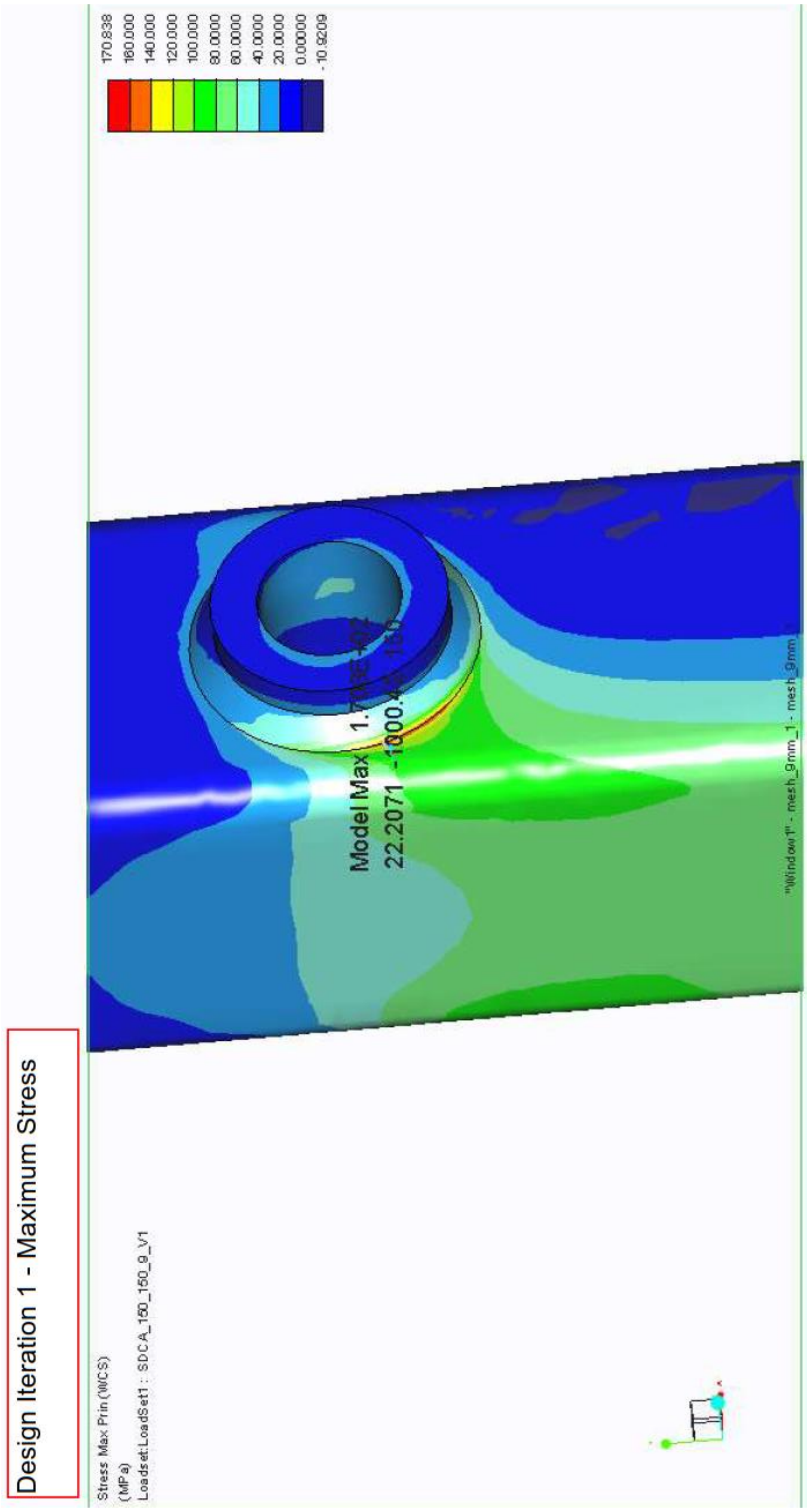


6. DRAWING 7001-0721 STRAP & BOLT CONNECTION

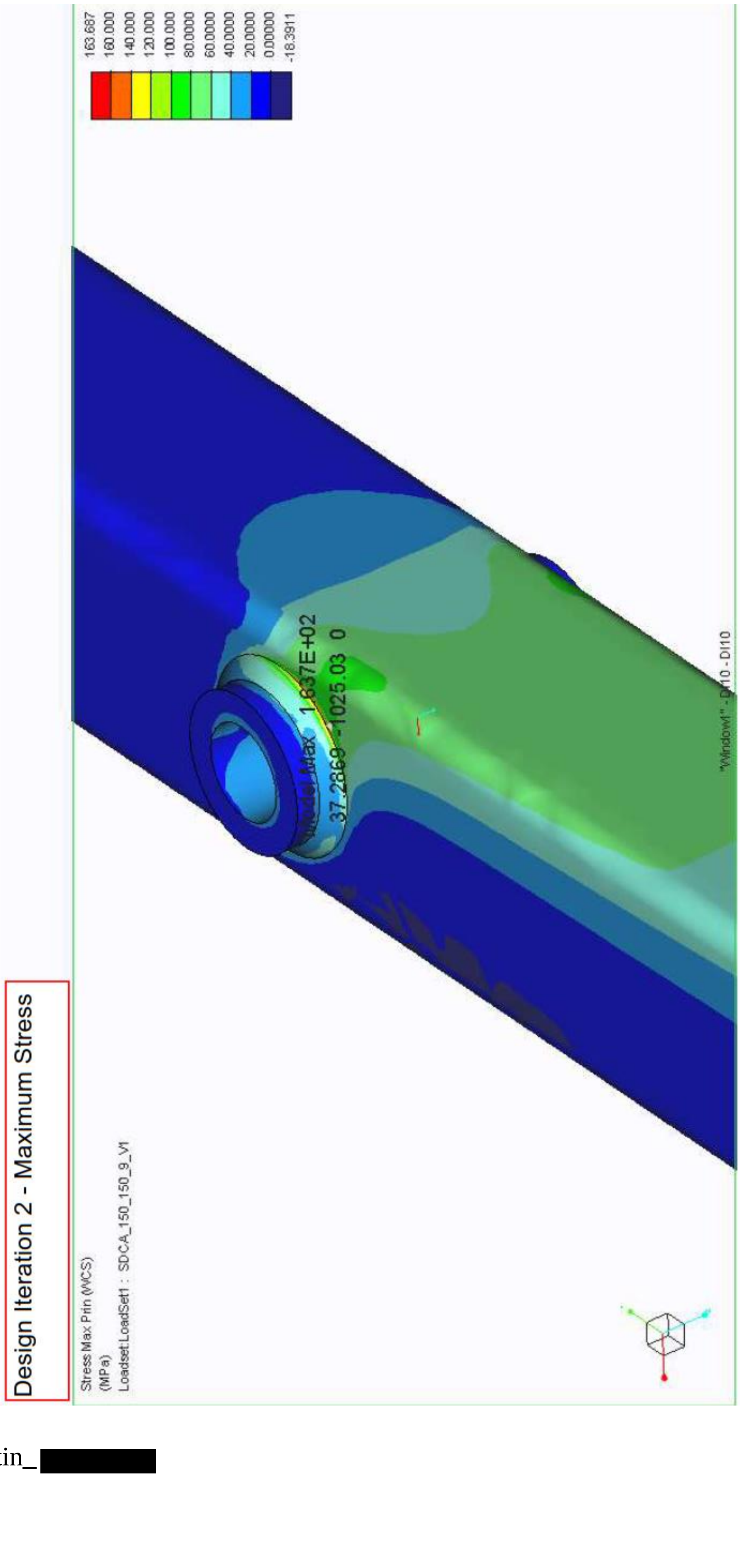


APPENDIX E

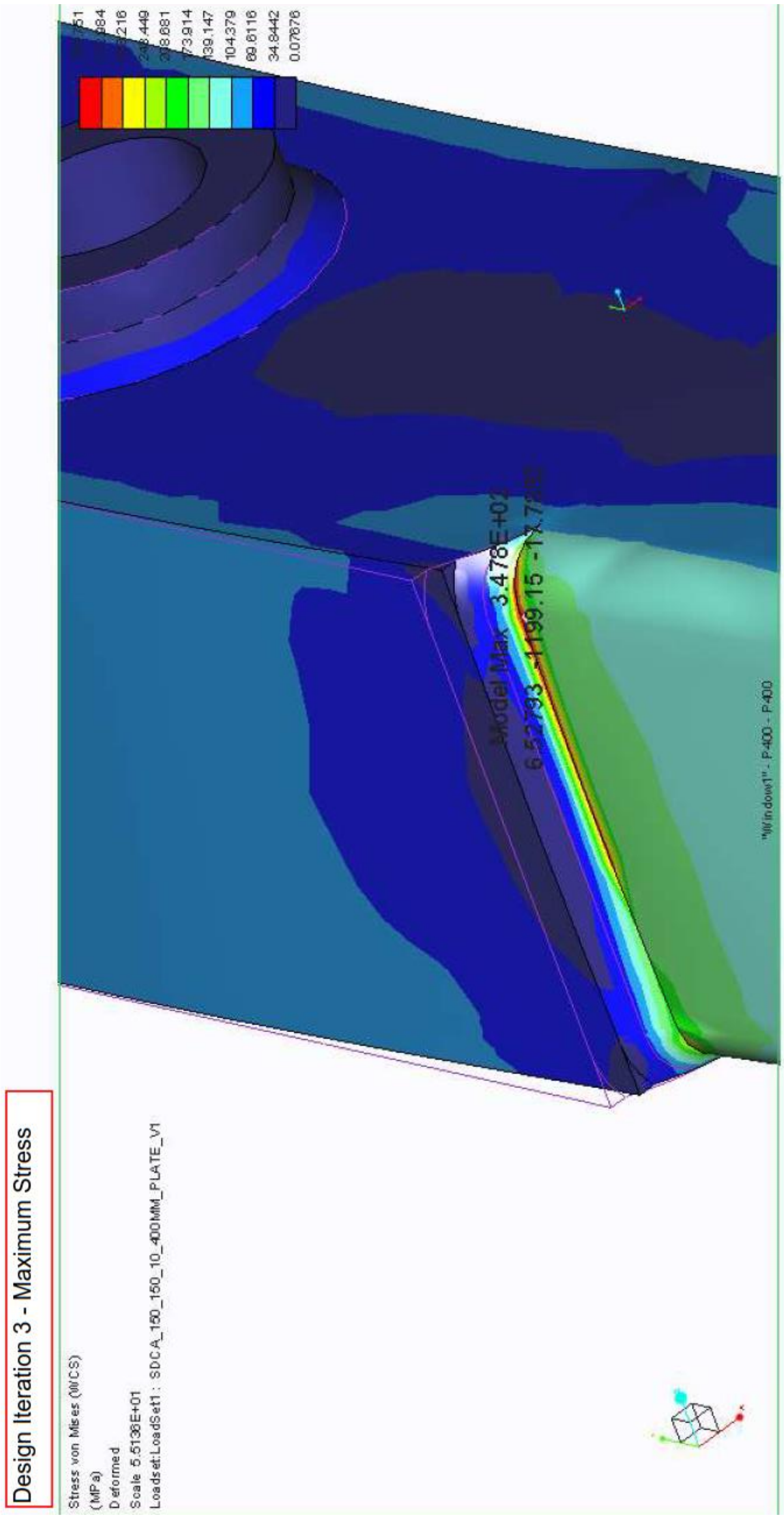
1. DESIGN ITERATION 1 – MAXIMUM STRESS



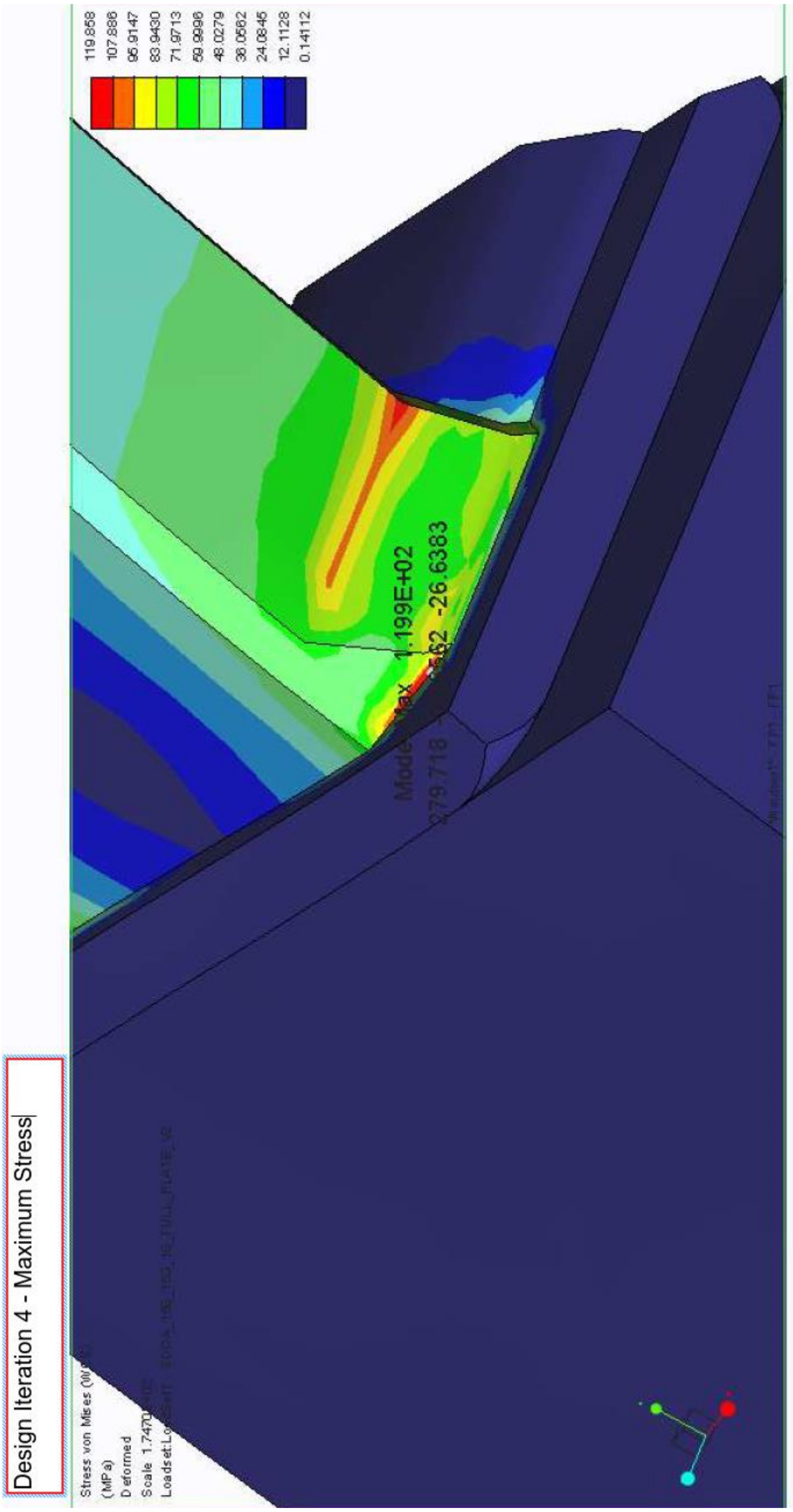
2. DESIGN ITERATION 2 – MAXIMUM STRESS



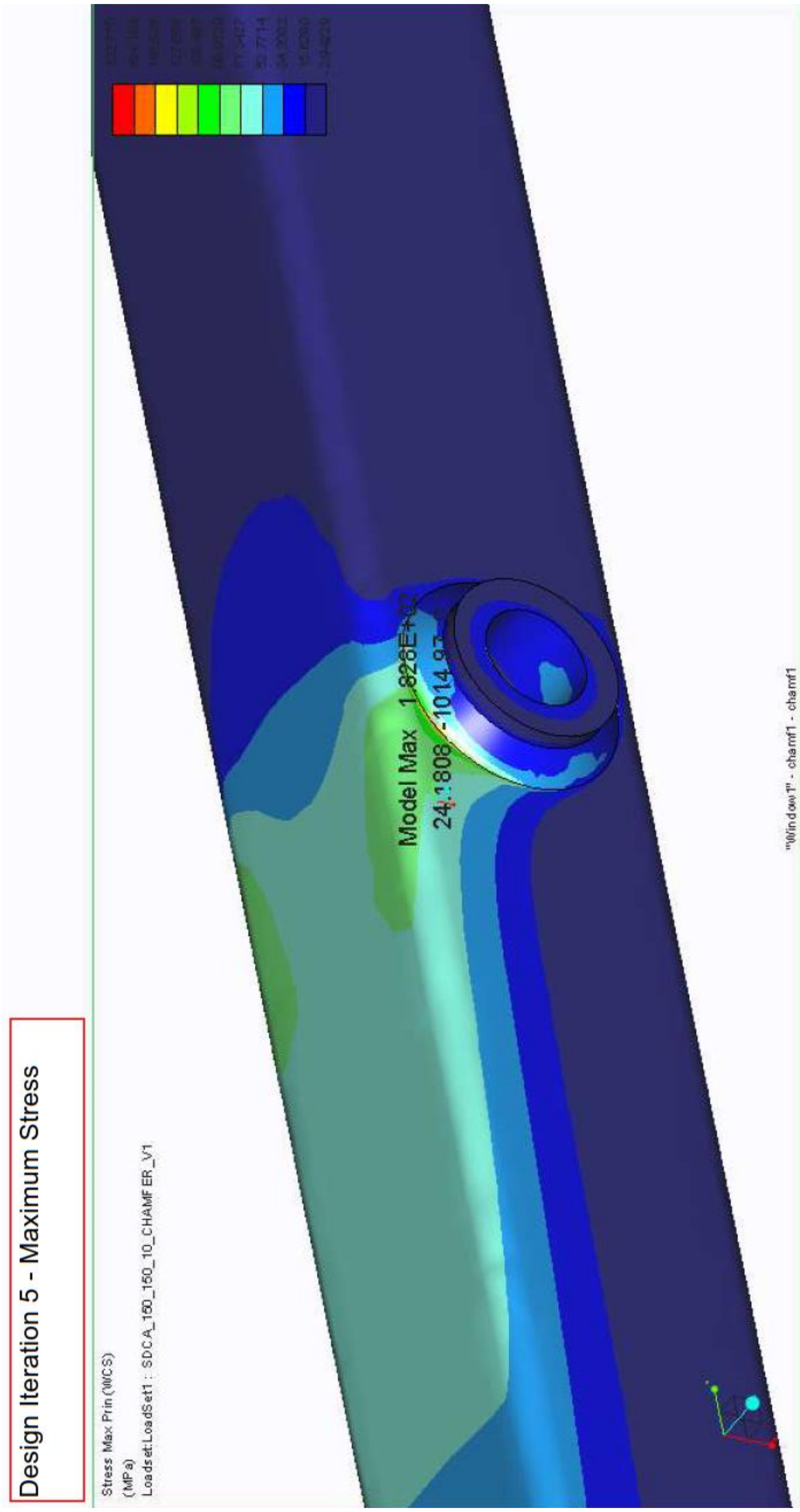
3. DESIGN ITERATION 3 – MAXIMUM STRESS



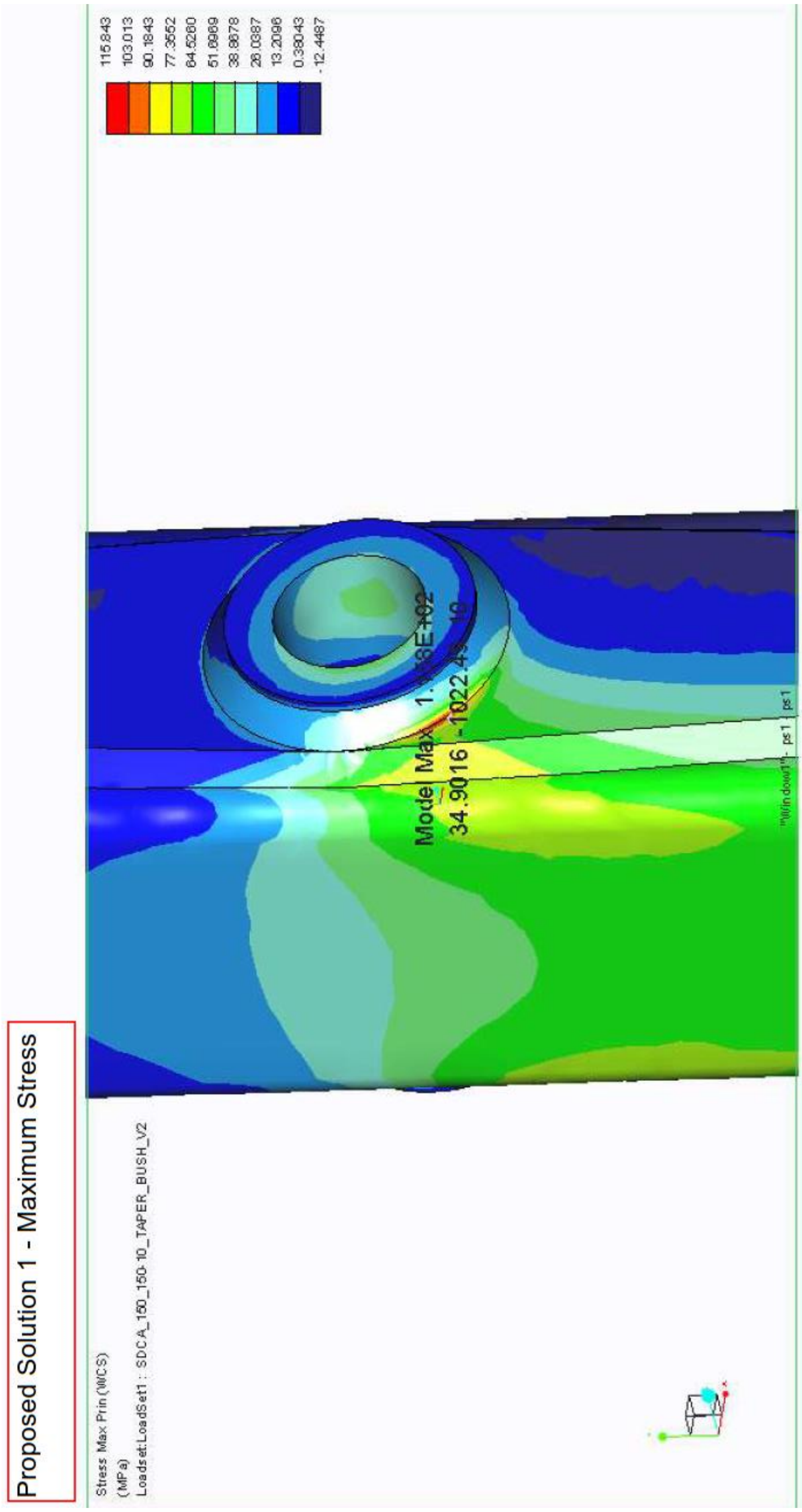
4. DESIGN ITERATION 4 – MAXIMUM STRESS



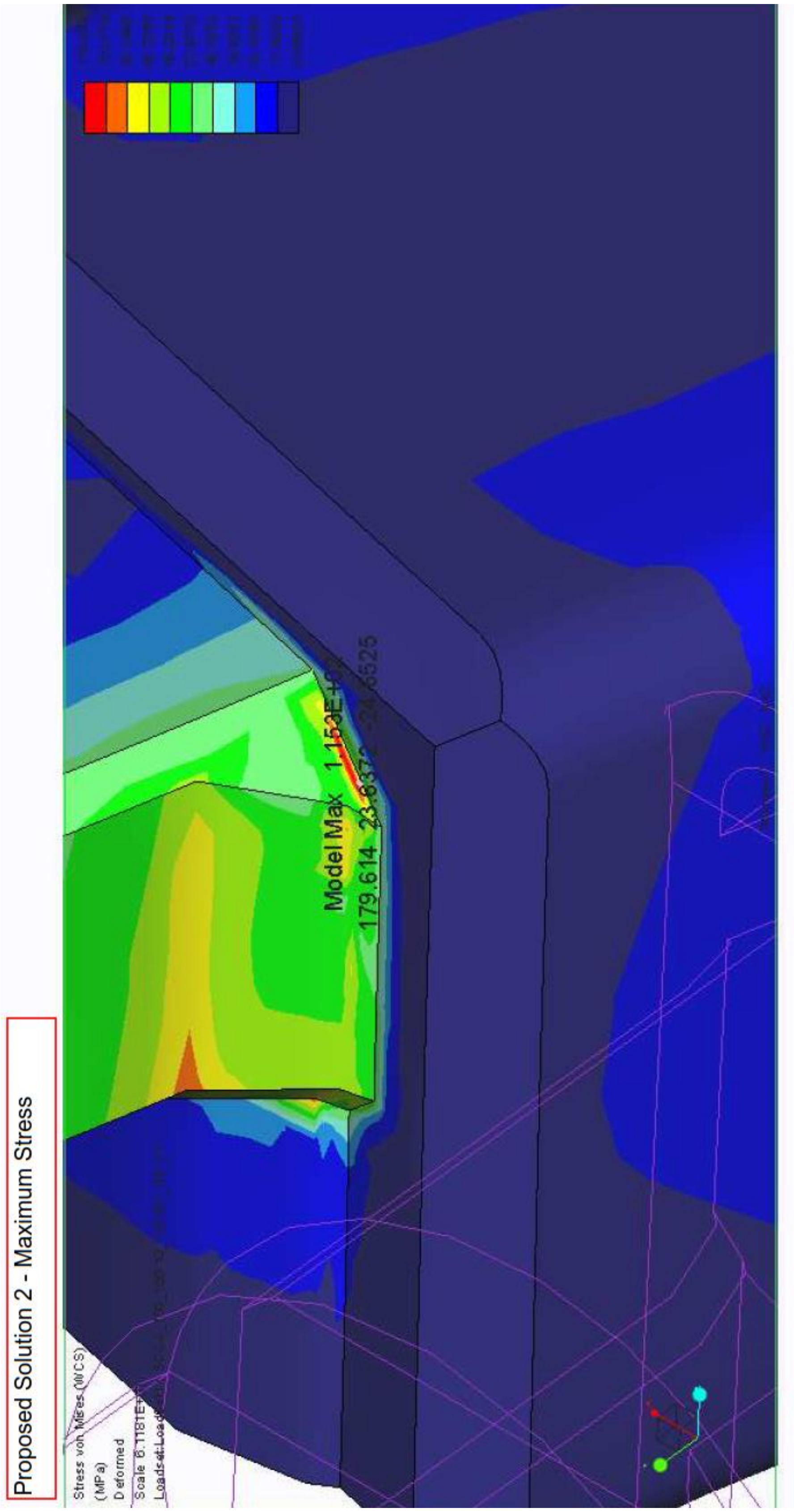
5. DESIGN ITERATION 5 – MAXIMUM STRESS



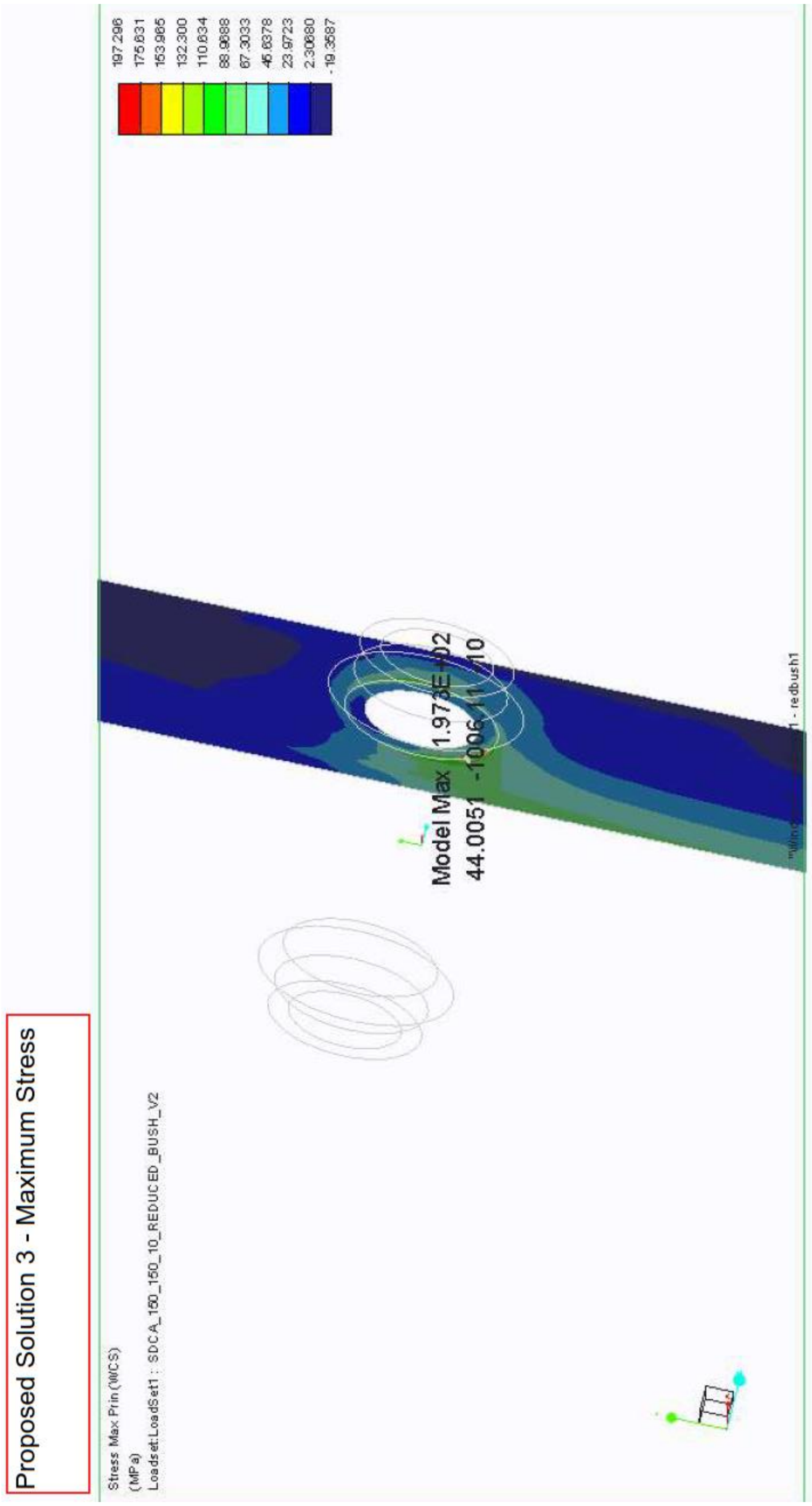
6. PROPOSED SOLUTION 1 – MAXIMUM STRESS



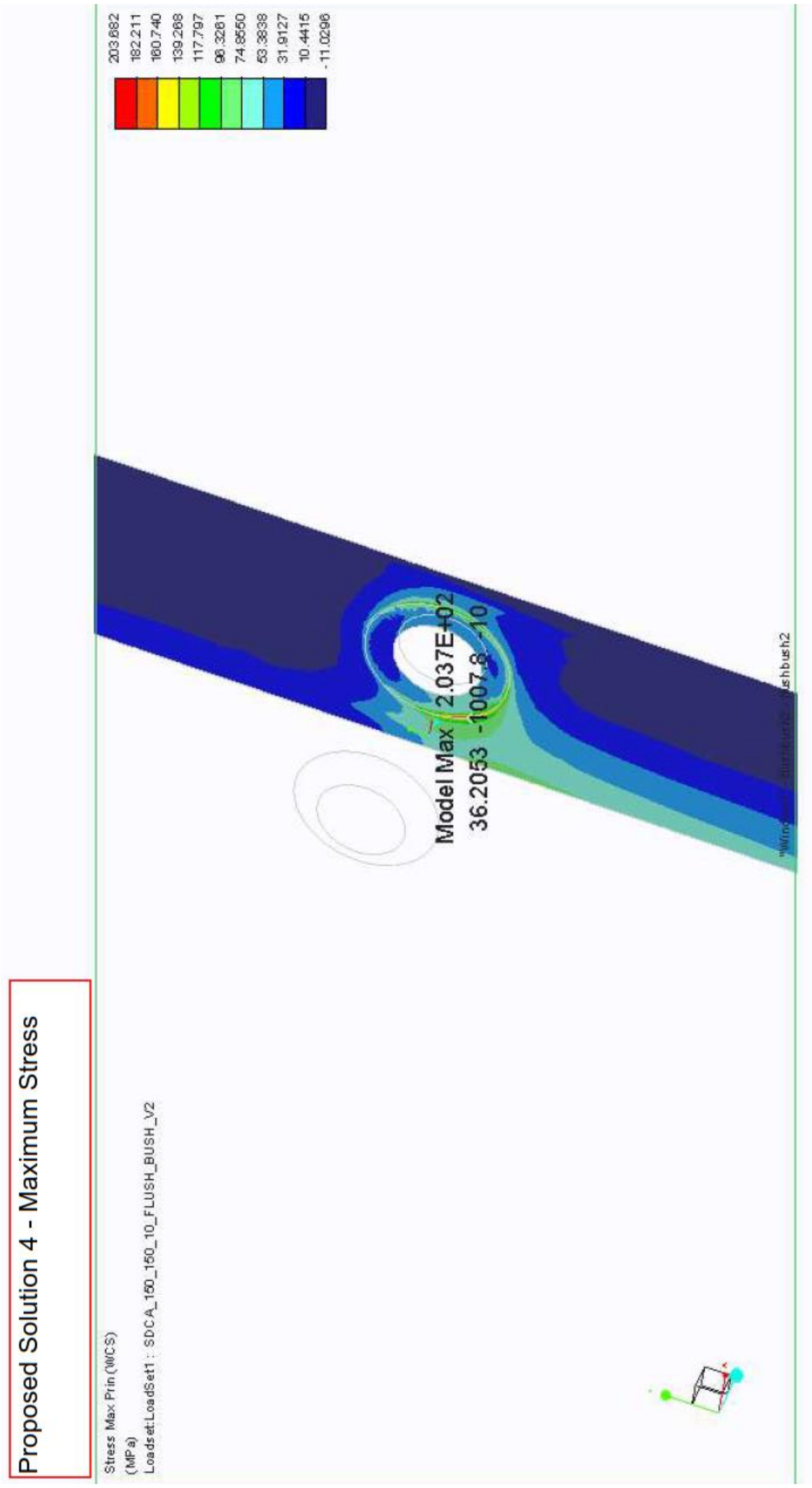
7. PROPOSED SOLUTION 2 – MAXIMUM STRESS



8. PROPOSED SOLUTION 3 – MAXIMUM STRESS



9. PROPOSED SOLUTION 4 – MAXIMUM STRESS



APPENDIX F

The following 5 pages contain the theoretical analysis calculations undertaken in Microsoft Excel.

SDCA Motion Calculations

Cycle Period (T)

n_{cycles}	48	Qty
t_z	8	s
τ	0.1667	s

Dimensions

AB	1.185	m	SDCA Above Pivot
BC	0.15	m	Connection Rod
CD	0.01	m	Eccentric Shaft Amplitude
AG	1.285	m	SDCA Below Pivot

Radians	Degrees
1.571	90
3.142	180
4.712	270
6.283	360

0.0175	Radian / Degree Ratio

					C relative to D		A relative to D		C relative to A										
Time (s)	θ_{CD} (R)	θ_{CD} (D)	Cos(θ_{CD})	Sin(θ_{CD})	CD_X (m)	CD_Y (m)	AD_X (m)	AD_Y (m)	AC_X (m)	AC_Y (m)	AC (m)	θ_{BAC} (R)	θ_{BAC} (D)	θ_{ABC} (R)	θ_{ABC} (D)	θ_{ACB} (R)	θ_{ACB} (D)	CE (m)	AE (m)
0.0000	0.000	0	1.0000	0.0000	0.0100	0.0000	-0.1497	-1.1850	0.1597	1.1850	1.1957	0.1258	7.2064	1.5792	90.4824	1.4366	82.3112	1.1850	0.1597
0.0023	0.087	5	0.9962	0.0872	0.0100	0.0009	-0.1497	-1.1850	0.1596	1.1859	1.1966	0.1257	7.2007	1.5850	90.8135	1.4309	81.9857	1.1859	0.1596
0.0046	0.175	10	0.9848	0.1736	0.0098	0.0017	-0.1497	-1.1850	0.1595	1.1867	1.1974	0.1256	7.1949	1.5907	91.1385	1.4254	81.6666	1.1867	0.1595
0.0069	0.262	15	0.9659	0.2588	0.0097	0.0026	-0.1497	-1.1850	0.1593	1.1876	1.1982	0.1255	7.1891	1.5962	91.4548	1.4199	81.3561	1.1876	0.1593
0.0093	0.349	20	0.9397	0.3420	0.0094	0.0034	-0.1497	-1.1850	0.1591	1.1884	1.1990	0.1254	7.1833	1.6015	91.7600	1.4147	81.0567	1.1884	0.1591
0.0116	0.436	25	0.9063	0.4226	0.0091	0.0042	-0.1497	-1.1850	0.1587	1.1892	1.1998	0.1253	7.1775	1.6066	92.0520	1.4097	80.7706	1.1892	0.1587
0.0139	0.524	30	0.8660	0.5000	0.0087	0.0050	-0.1497	-1.1850	0.1583	1.1900	1.2005	0.1252	7.1719	1.6114	92.3283	1.4050	80.4998	1.1900	0.1583
0.0162	0.611	35	0.8192	0.5736	0.0082	0.0057	-0.1497	-1.1850	0.1579	1.1907	1.2012	0.1251	7.1665	1.6159	92.5870	1.4006	80.2466	1.1907	0.1579
0.0185	0.698	40	0.7660	0.6428	0.0077	0.0064	-0.1497	-1.1850	0.1573	1.1914	1.2018	0.1250	7.1614	1.6201	92.8260	1.3965	80.0127	1.1914	0.1573
0.0208	0.785	45	0.7071	0.7071	0.0071	0.0071	-0.1497	-1.1850	0.1567	1.1921	1.2023	0.1249	7.1566	1.6239	93.0435	1.3928	79.7999	1.1921	0.1567
0.0231	0.873	50	0.6428	0.7660	0.0064	0.0077	-0.1497	-1.1850	0.1561	1.1927	1.2028	0.1248	7.1523	1.6273	93.2379	1.3895	79.6098	1.1927	0.1561
0.0255	0.960	55	0.5736	0.8192	0.0057	0.0082	-0.1497	-1.1850	0.1554	1.1932	1.2033	0.1248	7.1484	1.6303	93.4077	1.3866	79.4439	1.1932	0.1554
0.0278	1.047	60	0.5000	0.8660	0.0050	0.0087	-0.1497	-1.1850	0.1547	1.1937	1.2036	0.1247	7.1451	1.6328	93.5515	1.3841	79.3034	1.1937	0.1547
0.0301	1.134	65	0.4226	0.9063	0.0042	0.0091	-0.1497	-1.1850	0.1539	1.1941	1.2039	0.1247	7.1424	1.6348	93.6682	1.3821	79.1894	1.1941	0.1539
0.0324	1.222	70	0.3420	0.9397	0.0034	0.0094	-0.1497	-1.1850	0.1531	1.1944	1.2042	0.1246	7.1403	1.6364	93.7571	1.3806	79.1026	1.1944	0.1531
0.0347	1.309	75	0.2588	0.9659	0.0026	0.0097	-0.1497	-1.1850	0.1523	1.1947	1.2043	0.1246	7.1389	1.6374	93.8173	1.3796	79.0439	1.1947	0.1523
0.0370	1.396	80	0.1736	0.9848	0.0017	0.0098	-0.1497	-1.1850	0.1514	1.1948	1.2044	0.1246	7.1382	1.6380	93.8484	1.3790	79.0135	1.1948	0.1514
0.0394	1.484	85	0.0872	0.9962	0.0009	0.0100	-0.1497	-1.1850	0.1505	1.1950	1.2044	0.1246	7.1381	1.6380	93.8501	1.3790	79.0118	1.1950	0.1505
0.0417	1.571	90	0.0000	1.0000	0.0000	0.0100	-0.1497	-1.1850	0.1497	1.1950	1.2043	0.1246	7.1388	1.6375	93.8226	1.3795	79.0387	1.1950	0.1497
0.0440	1.658	95	-0.0872	0.9962	-0.0009	0.0100	-0.1497	-1.1850	0.1488	1.1950	1.2042	0.1246	7.1401	1.6365	93.7658	1.3805	79.0940	1.1950	0.1488
0.0463	1.745	100	-0.1736	0.9848	-0.0017	0.0098	-0.1497	-1.1850	0.1479	1.1948	1.2040	0.1247	7.1421	1.6350	93.6804	1.3819	79.1774	1.1948	0.1479
0.0486	1.833	105	-0.2588	0.9659	-0.0026	0.0097	-0.1497	-1.1850	0.1471	1.1947	1.2037	0.1247	7.1448	1.6331	93.5670	1.3838	79.2882	1.1947	0.1471
0.0509	1.920	110	-0.3420	0.9397	-0.0034	0.0094	-0.1497	-1.1850	0.1462	1.1944	1.2033	0.1248	7.1480	1.6306	93.4264	1.3862	79.4256	1.1944	0.1462
0.0532	2.007	115	-0.4226	0.9063	-0.0042	0.0091	-0.1497	-1.1850	0.1454	1.1941	1.2029	0.1248	7.1518	1.6277	93.2597	1.3891	79.5885	1.1941	0.1454
0.0556	2.094	120	-0.5000	0.8660	-0.0050	0.0087	-0.1497	-1.1850	0.1447	1.1937	1.2024	0.1249	7.1561	1.6243	93.0682	1.3923	79.7757	1.1937	0.1447
0.0579	2.182	125	-0.5736	0.8192	-0.0057	0.0082	-0.1497	-1.1850	0.1439	1.1932	1.2018	0.1250	7.1608	1.6206	92.8534	1.3960	79.9858	1.1932	0.1439
0.0602	2.269	130	-0.6428	0.7660	-0.0064	0.0077	-0.1497	-1.1850	0.1432	1.1927	1.2012	0.1251	7.1658	1.6165	92.6169	1.4001	80.2173	1.1927	0.1432
0.0625	2.356	135	-0.7071	0.7071	-0.0071	0.0071	-0.1497	-1.1850	0.1426	1.1921	1.2006	0.1252	7.1712	1.6120	92.3605	1.4044	80.4683	1.1921	0.1426
0.0648	2.443	140	-0.7660	0.6428	-0.0077	0.0064	-0.1497	-1.1850	0.1420	1.1914	1.1999	0.1253	7.1768	1.6072	92.0862	1.4091	80.7370	1.1914	0.1420
0.0671	2.531	145	-0.8192	0.5736	-0.0082	0.0057	-0.1497	-1.1850	0.1415	1.1907	1.1991	0.1254	7.1826	1.6021	91.7960	1.4141	81.0214	1.1907	0.1415
0.0694	2.618	150	-0.8660	0.5000	-0.0087	0.0050	-0.1497	-1.1850	0.1410	1.1900	1.1983	0.1255	7.1884	1.5968	91.4922	1.4193	81.3194	1.1900	0.1410
0.0718	2.705	155	-0.9063	0.4226	-0.0091	0.0042	-0.1497	-1.1850	0.1406	1.1892	1.1975	0.1256	7.1942	1.5913	91.1771	1.4247	81.6286	1.1892	0.1406
0.0741	2.793	160	-0.9397	0.3420	-0.0094	0.0034	-0.1497	-1.1850	0.1403	1.1884	1.1967	0.1257	7.2000	1.5857	90.8531	1.4302	81.9468	1.1884	0.1403
0.0764	2.880	165	-0.9659	0.2588	-0.0097	0.0026	-0.1497	-1.1850	0.1400	1.1876	1.1958	0.1258	7.2057	1.5799	90.5226	1.4359	82.2716	1.1876	0.1400
0.0787	2.967	170	-0.9848	0.1736	-0.0098	0.0017	-0.1497	-1.1850	0.1398	1.1867	1.1949	0.1259	7.2113	1.5741	90.1882	1.4417	82.6006	1.1867	0.1398
0.0810	3.054	175	-0.9962	0.0872	-0.0100	0.0009	-0.1497	-1.1850	0.1397	1.1859	1.1941	0.1260	7.2166	1.5682	89.8523	1.4474	82.9311	1.1859	0.1397
0.0833	3.142	180	-1.0000	0.0000	-0.0100	0.0000	-0.1497	-1.1850	0.1397	1.1850	1.1932	0.1260	7.2216	1.5624	89.5176	1.4532	83.2608	1.1850	0.1397
0.0856	3.229	185	-0.9962	-0.0872	-0.0100	-0.0009	-0.1497	-1.1850	0.1397	1.1841	1.1923	0.1261	7.2264	1.5566	89.1865	1.4589	83.5871	1.1841	0.1397
0.0880	3.316	190	-0.9848	-0.1736	-0.0098	-0.0017	-0.1497	-1.1850	0.1398	1.1833	1.1915	0.1262	7.2308	1.5509	88.8615	1.4645	83.9076	1.1833	0.1398
0.0903	3.403	195	-0.9659	-0.2588	-0.0097	-0.0026	-0.1497	-1.1850	0.1400	1.1824	1.1907	0.1263	7.2350	1.5454	88.5452	1.4699	84.2198	1.1824	0.1400
0.0926	3.491	200	-0.9397	-0.3420	-0.0094	-0.0034	-0.1497	-1.1850	0.1403	1.1816	1.1899	0.1263	7.2387	1.5401	88.2400	1.4752	84.5213	1.1816	0.1403
0.0949	3.578	205	-0.9063	-0.4226	-0.0091	-0.0042	-0.1497	-1.1850	0.1406	1.1808	1.1891	0.1264	7.2422	1.5350	87.9480	1.4802	84.8098	1.1808	0.1406
0.0972	3.665	210	-0.8660	-0.5000	-0.0087	-0.0050	-0.1497	-1.1850	0.1410	1.1800	1.1884	0.1265	7.2452	1.5302	87.6717	1.4850	85.0831	1.1800	0.1410
0.0995	3.752	215	-0.8192	-0.5736	-0.0082	-0.0057	-0.1497	-1.1850	0.1415	1.1793	1.1877	0.1265	7.2480	1.5256	87.4130	1.4894	85.3390	1.1793	0.1415
0.1019	3.840	220	-0.7660	-0.6428	-0.0077	-0.0064	-0.1497	-1.1850	0.1420	1.1786	1.1871	0.1265	7.2504	1.5215	87.1740	1.4936	85.5756	1.1786	0.1420
0.1042	3.927	225	-0.7071	-0.7071	-0.0071	-0.0071	-0.1497	-1.1850	0.1426	1.1779	1.1865	0.1266	7.2524	1.5177	86.9565	1.4973	85.7911	1.1779	0.1426
0.1065	4.014	230	-0.6428	-0.7660	-0.0064	-0.0077	-0.1497	-1.1850	0.1432	1.1773	1.1860	0.1266	7.2542	1.5143	86.7621	1.5007	85.9837	1.1773	0.1432
0.1088	4.102	235	-0.5736	-0.8192	-0.0057	-0.0082	-0.1497	-1.1850	0.1439	1.1768	1.1856	0.1266	7.2557	1.5113	86.5923	1.5036	86.1520	1.1768	0.1439
0.1111	4.189	240	-0.5000	-0.8660	-0.0050	-0.0087	-0.1497	-1.1850	0.1447	1.1763	1.1852	0.1267	7.2569	1.5088	86.4485	1.5061	86.2946	1.1763	0.1447
0.1134	4.276	245	-0.4226	-0.9063	-0.0042	-0.0091	-0.1497	-1.1850	0.1454	1.1759	1.1849	0.1267	7.2578	1.5068	86.3318	1.5081	86.4104	1.1759	0.1454
0.1157	4.363	250	-0.3420	-0.9397	-0.0034	-0.0094	-0.1497	-1.1850	0.1462	1.1756	1.1847	0.1267	7.2585	1.5052	86.2429	1.5097	86.4986	1.1756	0.1462
0.1181	4.451	255	-0.2588	-0.9659	-0.0026	-0.0097	-0.1497	-1.1850	0.1471	1.1753	1.1845	0.1267	7.2590	1.5042	86.1827	1.5107	86.5583	1.1753	0.1471
0.1204	4.538	260	-0.1736	-0.9848	-0.0017	-0.0098	-0.1497	-1.1850	0.1479	1.1752	1.1844	0.1267	7.2592	1.5036	86.1516	1.5113	86.5892	1.1752	0.1479
0.1227	4.625	265	-0.0872	-0.9962	-0.0009	-0.0100	-0.1497	-1.1850	0.1488	1.1750	1.1844	0.1267	7.2592	1.5036	86.1499	1.5113	86.5909	1.1750	0.1488
0.1250	4.712	270	0.0000	-1.0000	0.0000	-0.0100	-0.1497	-1.1850	0.1497	1.1750	1.1845	0.1267	7.2590	1.5041	86.1774	1.5108	86.5636	1.1750	0.1497
0.1273	4.800	275	0.0872	-0.9962	0.0009	-0.0100	-0.1497	-1.1850	0.1505	1.1750	1.1846	0.1267	7.2586	1.5051	86.2342	1.5098	86.5073	1.1750	0.1505
0.1296	4.887	280	0.1736	-0.9848	0.0017	-0.0098	-0.1497	-1.1850	0.1514	1.1752	1.1849	0.1267	7.2579	1.5066	86.3196	1.5084	86.4226	1.1752	0.1514
0.1319	4.974	285	0.2588	-0.9659	0.0026	-0.0097	-0.1497	-1.1850	0.1523	1.1753	1.1852	0.1267	7.2570	1.5085	86.4330	1.5064	86.3100	1.1753	0.1523
0.1343	5.061	290	0.3420	-0.9397	0.0034	-0.0094	-0.1497	-1.1850	0.1531	1.1756	1.1855	0.1266	7.2558	1.5110	86.5736	1.5040	86.1706	1.1756	0.1531
0.1366	5.149	295	0.4226	-0.9063	0.0042	-0.0091	-0.1497	-1.1850	0.1539	1.1759	1.1860	0.1266	7.2544	1.5139	86.7403	1.5011	86.0053	1.1759	0.1539
0.1389	5.236	300	0.5000	-0.8660	0.0050	-0.0087	-0.1497	-1.1850	0.1547	1.1763	1.1865	0.1266	7.2527	1.5172	86.9318	1.4978	85.8156	1.1763	0.1547
0.1412	5.323	305	0.5736	-0.8192	0.0057	-0.0082	-0.1497	-1.1850	0.1554	1.1768	1.1870	0.1265	7.2506	1.5210	87.1466	1.4941	85.6028	1.1768	0.1554
0.1435	5.411	310	0.6428	-0.7660	0.0064	-0.0077	-0.1497	-1.1850	0.1561	1.1773	1.1876	0.1265	7.2483	1.5251	87.3831	1.4900	85.3686	1.1773	0.1561
0.1458	5.498	315	0.7071	-0.7071	0.0071	-0.0071	-0.1497	-1.1850	0.1567	1.1779	1.1883	0.1265	7.2456	1.5296	87.6395	1.4855	85.1149	1.1779	0.1567
0.1481	5.585	320	0.7660	-0.6428	0.0077	-0.0064	-0.1497	-1.1850	0.1573	1.1786	1.1890	0.1264	7.2426	1.5344	87.9138	1.4808	84.8436	1.1786	0.1573
0.1505	5.672	325	0.8192	-0.5736	0.0082	-0.0057	-0.1497	-1.1850	0.1579	1.1793	1.1898	0.1263	7.2392	1.5395	88.2040	1.4758	84.5568	1.1793	0.1579
0.1528	5.760	330	0.8660	-0.5000	0.0087	-0.0050	-0.1497	-1.1850	0.1583	1.1800	1.1906	0.1263	7.2354	1.5448	88.5078	1.4706	84.2568	1.1800	0.1583
0.1551	5.847	335	0.9063	-0.4226	0.0091	-0.0042	-0.1497	-1.1850	0.1587	1.1808	1.1914	0.1262	7.2314	1.5503	88.8229	1.4651	83.9458	1.1808	0.1587
0.1574	5.934	340	0.9397	-0.3420	0.0094	-0.0034	-0.1497	-1.1850	0.1591	1.1816	1.1922	0.1261	7.2269	1.5559	89.1469	1.4596	83.6262	1.1816	0.1591
0.1597	6.021	345	0.9659	-0.2588	0.0097	-0.0026	-0.1497	-1.1850	0.1593	1.1824	1.1931	0.1261	7.2222	1.5617	89.4774	1.4539	83.3004	1.1824	0.1593
0.1620	6.109	350	0.9848	-0.1736	0.0098	-0.0017	-0.1497	-1.1850	0.1595	1.1833	1.1940	0.1260	7.2172	1.5675	89.8118	1.4481	82.9710	1.1833	0.1595
0.1644	6.196	355	0.9962	-0.0872	0.0100	-0.0009	-0.1497	-1.1850	0.1596	1.1841	1.1948	0.1259	7.2119	1.5734	90.1477	1.4423	82.6404	1.1841	0.1596
0.1667	6.283	360	1.0000	0.0000	0.0100	0.0000	-0.1497	-1.1850	0.1597	1.1850	1.1957	0.1258	7.2064	1.5792	90.4824	1.4366	82.3112	1.1850	0.1597

I_{BA}	24.79	$kg.m^2$
I_{GA}	3119.00	$kg.m^2$

								Above Pin							
				C relative to B		B relative to D		Position		Velocity		Acceleration			Moment
θ_{ACE} (R)	θ_{ACE} (D)	θ_{BCF} (R)	θ_{BCF} (D)	BC_X (m)	BC_Y (m)	BD_X (m)	BD_Y (m)	s_{BA} (m)	θ_{BA} (rad)	v_{BA}(m/s)	ω_{BA}(rad/s)	$(a_t)_{BA}$ (m/s^2)	$(a_n)_{BA}$ (m/s^2)	α_{BA} (rad/s^2)	M_{BA} (Nm)
0.1339	7.6738	0.0003	0.0151	0.1500	0.000039	0.1400	-0.000039	0.0097	0.0082	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.1338	7.6664	0.0061	0.3479	0.1500	0.000911	0.1400	-0.000039	0.0096	0.0081	-0.0152	-0.0129	-6.5866	0.0002	-5.5583	-137.8025
0.1336	7.6555	0.0118	0.6779	0.1500	0.001775	0.1401	-0.000038	0.0095	0.0080	-0.0459	-0.0387	-13.2206	0.0018	-11.1566	-276.5949
0.1334	7.6411	0.0175	1.0028	0.1500	0.002625	0.1403	-0.000037	0.0093	0.0079	-0.0762	-0.0643	-13.1034	0.0049	-11.0577	-274.1431
0.1331	7.6234	0.0230	1.3199	0.1500	0.003455	0.1406	-0.000035	0.0091	0.0077	-0.1061	-0.0895	-12.9064	0.0095	-10.8915	-270.0218
0.1327	7.6025	0.0284	1.6270	0.1499	0.004259	0.1409	-0.000033	0.0088	0.0074	-0.1353	-0.1142	-12.6295	0.0154	-10.6578	-264.2278
0.1323	7.5786	0.0335	1.9216	0.1499	0.005030	0.1413	-0.000030	0.0084	0.0071	-0.1637	-0.1381	-12.2725	0.0226	-10.3565	-256.7593
0.1318	7.5518	0.0384	2.2017	0.1499	0.005763	0.1417	-0.000027	0.0080	0.0067	-0.1911	-0.1613	-11.8355	0.0308	-9.9878	-247.6172
0.1313	7.5223	0.0430	2.4650	0.1499	0.006451	0.1422	-0.000024	0.0075	0.0063	-0.2173	-0.1834	-11.3188	0.0398	-9.5518	-236.8071
0.1307	7.4905	0.0473	2.7096	0.1498	0.007091	0.1428	-0.000020	0.0069	0.0058	-0.2421	-0.2043	-10.7230	0.0495	-9.0489	-224.3408
0.1301	7.4564	0.0512	2.9337	0.1498	0.007677	0.1434	-0.000017	0.0063	0.0053	-0.2654	-0.2240	-10.0489	0.0594	-8.4801	-210.2385
0.1295	7.4205	0.0547	3.1356	0.1498	0.008205	0.1440	-0.000013	0.0056	0.0047	-0.2869	-0.2421	-9.2981	0.0695	-7.8465	-194.5307
0.1289	7.3829	0.0578	3.3137	0.1497	0.008670	0.1447	-0.000010	0.0049	0.0041	-0.3065	-0.2587	-8.4726	0.0793	-7.1499	-177.2606
0.1282	7.3439	0.0605	3.4668	0.1497	0.009070	0.1455	-0.000007	0.0042	0.0035	-0.3241	-0.2735	-7.5752	0.0886	-6.3926	-158.4854
0.1275	7.3038	0.0627	3.5936	0.1497	0.009402	0.1463	-0.000005	0.0034	0.0029	-0.3394	-0.2864	-6.6094	0.0972	-5.5776	-138.2790
0.1268	7.2630	0.0645	3.6932	0.1497	0.009662	0.1471	-0.000003	0.0026	0.0022	-0.3523	-0.2973	-5.5795	0.1047	-4.7085	-116.7326
0.1260	7.2216	0.0657	3.7649	0.1497	0.009849	0.1479	-0.000001	0.0017	0.0015	-0.3627	-0.3060	-4.4909	0.1110	-3.7898	-93.9566
0.1253	7.1801	0.0665	3.8081	0.1497	0.009962	0.1488	0.000000	0.0009	0.0007	-0.3704	-0.3126	-3.3497	0.1158	-2.8268	-70.0809
0.1246	7.1388	0.0667	3.8226	0.1497	0.010000	0.1497	0.000000	0.0000	0.0000	-0.3754	-0.3168	-2.1631	0.1189	-1.8254	-45.2555
0.1239	7.0978	0.0665	3.8081	0.1497	0.009962	0.1505	0.000000	-0.0009	-0.0007	-0.3776	-0.3186	-0.9392	0.1203	-0.7926	-19.6498
0.1232	7.0577	0.0657	3.7649	0.1497	0.009849	0.1514	-0.000001	-0.0017	-0.0015	-0.3769	-0.3180	0.3129	0.1199	0.2641	6.5473
0.1225	7.0185	0.0645	3.6932	0.1497	0.009662	0.1523	-0.000003	-0.0026	-0.0022	-0.3732	-0.3149	1.5835	0.1175	1.3363	33.1295
0.1218	6.9807	0.0627	3.5936	0.1497	0.009402	0.1531	-0.000005	-0.0035	-0.0029	-0.3666	-0.3094	2.8619	0.1134	2.4151	59.8745
0.1212	6.9446	0.0605	3.4669	0.1497	0.009071	0.1540	-0.000008	-0.0043	-0.0036	-0.3570	-0.3013	4.1367	0.1076	3.4909	86.5465
0.1206	6.9103	0.0578	3.3140	0.1497	0.008671	0.1547	-0.000011	-0.0051	-0.0043	-0.3445	-0.2907	5.3963	0.1002	4.5538	112.8987
0.1200	6.8782	0.0547	3.1360	0.1498	0.008206	0.1555	-0.000014	-0.0058	-0.0049	-0.3292	-0.2778	6.6284	0.0914	5.5936	138.6770
0.1195	6.8484	0.0512	2.9343	0.1498	0.007679	0.1562	-0.000018	-0.0066	-0.0055	-0.3111	-0.2625	7.8208	0.0817	6.5998	163.6231
0.1191	6.8213	0.0473	2.7104	0.1498	0.007093	0.1569	-0.000022	-0.0072	-0.0061	-0.2903	-0.2450	8.9610	0.0711	7.5620	187.4784
0.1186	6.7970	0.0430	2.4660	0.1499	0.006454	0.1575	-0.000026	-0.0079	-0.0066	-0.2671	-0.2254	10.0369	0.0602	8.4700	209.9882
0.1183	6.7757	0.0384	2.2029	0.1499	0.005766	0.1581	-0.000030	-0.0084	-0.0071	-0.2415	-0.2038	11.0367	0.0492	9.3137	230.9055
0.1179	6.7576	0.0336	1.9230	0.1499	0.005033	0.1586	-0.000033	-0.0089	-0.0075	-0.2139	-0.1805	11.9492	0.0386	10.0837	249.9952
0.1177	6.7428	0.0284	1.6286	0.1499	0.004263	0.1590	-0.000037	-0.0093	-0.0079	-0.1843	-0.1556	12.7638	0.0287	10.7711	267.0380
0.1175	6.7315	0.0231	1.3217	0.1500	0.003460	0.1594	-0.000040	-0.0097	-0.0082	-0.1532	-0.1292	13.4710	0.0198	11.3680	281.8344
0.1174	6.7237	0.0175	1.0047	0.1500	0.002630	0.1596	-0.000042	-0.0100	-0.0084	-0.1206	-0.1018	14.0625	0.0123	11.8670	294.2079
0.1173	6.7195	0.0119	0.6800	0.1500	0.001780	0.1598	-0.000044	-0.0102	-0.0086	-0.0870	-0.0734	14.5309	0.0064	12.2624	304.0085
0.1173	6.7189	0.0061	0.3500	0.1500	0.000916	0.1600	-0.000045	-0.0103	-0.0087	-0.0525	-0.0443	14.8706	0.0023	12.5490	311.1155
0.1173	6.7220	0.0003	0.0172	0.1500	0.000045	0.1600	-0.000045	-0.0103	-0.0087	-0.0176	-0.0149	15.0773	0.0003	12.7234	315.4395
0.1174	6.7287	-0.0055	-0.3158	0.1500	-0.000827	0.1600	-0.000045	-0.0103	-0.0087	0.0174	0.0147	15.1483	0.0003	12.7833	316.9246
0.1176	6.7390	-0.0113	-0.6466	0.1500	-0.001693	0.1598	-0.000044	-0.0102	-0.0086	0.0523	0.0442	15.0825	0.0023	12.7279	315.5495
0.1179	6.7528	-0.0170	-0.9726	0.1500	-0.002546	0.1596	-0.000042	-0.0100	-0.0084	0.0868	0.0732	14.8807	0.0064	12.5576	311.3279
0.1182	6.7701	-0.0225	-1.2914	0.1500	-0.003381	0.1594	-0.000040	-0.0097	-0.0082	0.1204	0.1016	14.5452	0.0122	12.2745	304.3088
0.1185	6.7906	-0.0279	-1.6004	0.1499	-0.004189	0.1590	-0.000037	-0.0093	-0.0079	0.1530	0.1291	14.0800	0.0198	11.8819	294.5754
0.1189	6.8143	-0.0331	-1.8974	0.1499	-0.004966	0.1586	-0.000034	-0.0089	-0.0075	0.1843	0.1555	13.4906	0.0287	11.3845	282.2441
0.1194	6.8410	-0.0380	-2.1800	0.1499	-0.005706	0.1581	-0.000030	-0.0084	-0.0071	0.2139	0.1805	12.7841	0.0386	10.7883	267.4624
0.1199	6.8704	-0.0427	-2.4461	0.1499	-0.006402	0.1575	-0.000026	-0.0079	-0.0066	0.2416	0.2039	11.9688	0.0492	10.1003	250.4059
0.1205	6.9024	-0.0470	-2.6935	0.1498	-0.007049	0.1569	-0.000022	-0.0072	-0.0061	0.2672	0.2254	11.0544	0.0602	9.3286	231.2756
0.1211	6.9367	-0.0510	-2.9204	0.1498	-0.007642	0.1562	-0.000018	-0.0066	-0.0055	0.2904	0.2451	10.0516	0.0712	8.4823	210.2942
0.1217	6.9730	-0.0545	-3.1250	0.1498	-0.008177	0.1555	-0.000014	-0.0058	-0.0049	0.3112	0.2626	8.9717	0.0817	7.5711	187.7016
0.1224	7.0110	-0.0577	-3.3056	0.1498	-0.008649	0.1548	-0.000011	-0.0051	-0.0043	0.3293	0.2779	7.8269	0.0915	6.6050	163.7509
0.1231	7.0505	-0.0604	-3.4610	0.1497	-0.009055	0.1540	-0.000008	-0.0043	-0.0036	0.3447	0.2909	6.6297	0.1002	5.5947	138.7040
0.1238	7.0912	-0.0627	-3.5898	0.1497	-0.009392	0.1531	-0.000005	-0.0035	-0.0029	0.3571	0.3014	5.3928	0.1076	4.5509	112.8266
0.1245	7.1327	-0.0644	-3.6910	0.1497	-0.009656	0.1523	-0.000003	-0.0026	-0.0022	0.3667	0.3095	4.1289	0.1135	3.4843	86.3839
0.1252	7.1747	-0.0657	-3.7639	0.1497	-0.009847	0.1514	-0.000001	-0.0017	-0.0015	0.3733	0.3150	2.8505	0.1176	2.4055	59.6363
0.1260	7.2169	-0.0665	-3.8079	0.1497	-0.009962	0.1505	0.000000	-0.0009	-0.0007	0.3769	0.3181	1.5695	0.1199	1.3244	32.8356
0.1267	7.2590	-0.0667	-3.8226	0.1497	-0.010000	0.1497	0.000000	0.0000	0.0000	0.3776	0.3187	0.2974	0.1203	0.2509	6.2211
0.1274	7.3006	-0.0665	-3.8079	0.1497	-0.009962	0.1488	0.000000	0.0009	0.0007	0.3754	0.3168	-0.9551	0.1189	-0.8060	-19.9830
0.1281	7.3414	-0.0657	-3.7639	0.1497	-0.009847	0.1479	-0.000001	0.0017	0.0015	0.3704	0.3125	-2.1782	0.1158	-1.8381	-45.5704
0.1288	7.3810	-0.0644	-3.6911	0.1497	-0.009656	0.1471	-0.000003	0.0026	0.0022	0.3626	0.3060	-3.3628	0.1109	-2.8378	-70.3540
0.1295	7.4193	-0.0627	-3.5899	0.1497	-0.009392	0.1463	-0.000005	0.0034	0.0029	0.3522	0.2972	-4.5010	0.1047	-3.7983	-94.1677
0.1301	7.4558	-0.0604	-3.4611	0.1497	-0.009056	0.1455	-0.000007	0.0042	0.0035	0.3392	0.2863	-5.5859	0.0971	-4.7139	-116.8660
0.1307	7.4903	-0.0577	-3.3059	0.1498	-0.008650	0.1448	-0.000010	0.0049	0.0041	0.3239	0.2734	-6.6116	0.0885	-5.5794	-138.3246
0.1313	7.5226	-0.0545	-3.1254	0.1498	-0.008178	0.1440	-0.000013	0.0056	0.0047	0.3064	0.2586	-7.5730	0.0792	-6.3907	-158.4394
0.1318	7.5523	-0.0510	-2.9210	0.1498	-0.007644	0.1434	-0.000017	0.0063	0.0053	0.2868	0.2420	-8.4662	0.0694	-7.1445	-177.1253
0.1323	7.5794	-0.0470	-2.6943	0.1498	-0.007051	0.1428	-0.000020	0.0069	0.0058	0.2653	0.2239	-9.2878	0.0594	-7.8378	-194.3145
0.1327	7.6034	-0.0427	-2.4470	0.1499	-0.006404	0.1422	-0.000024	0.0075	0.0063	0.2421	0.2043	-10.0354	0.0494	-8.4687	-209.9549
0.1331	7.6244	-0.0381	-2.1812	0.1499	-0.005709	0.1417	-0.000027	0.0080	0.0067	0.2173	0.1834	-10.7071	0.0398	-9.0355	-224.0079
0.1334	7.6420	-0.0331	-1.8988	0.1499	-0.004970	0.1413	-0.000030	0.0084	0.0071	0.1911	0.1613	-11.3016	0.0308	-9.5372	-236.4459
0.1336	7.6563	-0.0280	-1.6020	0.1499	-0.004194	0.1409	-0.000033	0.0088	0.0074	0.1638	0.1382	-11.8180	0.0226	-9.9730	-247.2505
0.1338	7.6670	-0.0226	-1.2932	0.1500	-0.003385	0.1406	-0.000035	0.0091	0.0077	0.1354	0.1143	-12.2558	0.0155	-10.3425	-256.4101
0.1339	7.6742	-0.0170	-0.9746	0.1500	-0.002551	0.1403	-0.000037	0.0093	0.0079	0.1062	0.0896	-12.6147	0.0095	-10.6453	-263.9181
0.1340	7.6777	-0.0113	-0.6487	0.1500	-0.001698	0.1401	-0.000038	0.0095	0.0080	0.0763	0.0644	-12.8944	0.0049	-10.8814	-269.7710
0.1340	7.6776	-0.0055	-0.3180	0.1500	-0.000832	0.1400	-0.000039	0.0096	0.0081	0.0460	0.0388	-13.0950	0.0018	-11.0506	-273.9667
0.1339	7.6738	0.0003	0.0151	0.1500	0.000039	0.1400	-0.000039	0.0097	0.0082	0.0154	0.0130	-13.2162	0.0002	-11.1529	-276.5038

Below Pin							
Position		Velocity		Acceleration			Moment
S_{GA} (m)	θ_{GA} (rad)	v_{GA}(m/s)	ω_{GA}(rad/s)	$(a_t)_{GA}$ (m/s^2)	$(a_n)_{GA}$ (m/s^2)	α_{GA} (rad/s^2)	M_{GA} (Nm)
-0.0105	-0.0082	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-0.0104	-0.0081	0.0165	0.0129	7.1425	0.0002	5.5583	17336.4805
-0.0103	-0.0080	0.0497	0.0387	14.3363	0.0019	11.1566	34797.5005
-0.0101	-0.0079	0.0826	0.0643	14.2092	0.0053	11.0577	34489.0523
-0.0099	-0.0077	0.1150	0.0895	13.9956	0.0103	10.8915	33970.5690
-0.0095	-0.0074	0.1467	0.1142	13.6953	0.0168	10.6578	33241.6441
-0.0091	-0.0071	0.1775	0.1381	13.3081	0.0245	10.3565	32302.0507
-0.0086	-0.0067	0.2072	0.1613	12.8343	0.0334	9.9878	31151.9170
-0.0081	-0.0063	0.2356	0.1834	12.2740	0.0432	9.5518	29791.9343
-0.0075	-0.0058	0.2626	0.2043	11.6279	0.0536	9.0489	28223.5907
-0.0068	-0.0053	0.2878	0.2240	10.8969	0.0644	8.4801	26449.4237
-0.0061	-0.0047	0.3111	0.2421	10.0828	0.0753	7.8465	24473.2796
-0.0053	-0.0041	0.3324	0.2587	9.1876	0.0860	7.1499	22300.5730
-0.0045	-0.0035	0.3514	0.2735	8.2145	0.0961	6.3926	19938.5329
-0.0037	-0.0029	0.3680	0.2864	7.1672	0.1054	5.5776	17396.4265
-0.0028	-0.0022	0.3820	0.2973	6.0504	0.1136	4.7085	14685.7504
-0.0019	-0.0015	0.3933	0.3060	4.8699	0.1204	3.7898	11820.3778
-0.0009	-0.0007	0.4017	0.3126	3.6324	0.1256	2.8268	8816.6556
0.0000	0.0000	0.4071	0.3168	2.3456	0.1290	1.8254	5693.4420
0.0009	0.0007	0.4095	0.3186	1.0185	0.1305	0.7926	2472.0804
0.0019	0.0015	0.4087	0.3180	-0.3394	0.1300	-0.2641	-823.6942
0.0028	0.0022	0.4047	0.3149	-1.7171	0.1275	-1.3363	-4167.9166
0.0038	0.0029	0.3975	0.3094	-3.1034	0.1230	-2.4151	-7532.6208
0.0046	0.0036	0.3871	0.3013	-4.4858	0.1166	-3.4909	-10888.1328
0.0055	0.0043	0.3736	0.2907	-5.8517	0.1086	-4.5538	-14203.4221
0.0063	0.0049	0.3570	0.2778	-7.1878	0.0992	-5.5936	-17446.5044
0.0071	0.0055	0.3373	0.2625	-8.4808	0.0885	-6.5998	-20584.8867
0.0078	0.0061	0.3148	0.2450	-9.7172	0.0771	-7.5620	-23586.0461
0.0085	0.0066	0.2896	0.2254	-10.8839	0.0653	-8.4700	-26417.9298
0.0091	0.0071	0.2619	0.2038	-11.9681	0.0534	-9.3137	-29049.4668
0.0097	0.0075	0.2319	0.1805	-12.9576	0.0419	-10.0837	-31451.0795
0.0101	0.0079	0.1999	0.1556	-13.8409	0.0311	-10.7711	-33595.1841
0.0105	0.0082	0.1661	0.1292	-14.6078	0.0215	-11.3680	-35456.6689
0.0108	0.0084	0.1308	0.1018	-15.2492	0.0133	-11.8670	-37013.3400
0.0110	0.0086	0.0943	0.0734	-15.7571	0.0069	-12.2624	-38246.3253
0.0112	0.0087	0.0570	0.0443	-16.1255	0.0025	-12.5490	-39140.4271
0.0112	0.0087	0.0191	0.0149	-16.3496	0.0003	-12.7234	-39684.4154
0.0112	0.0087	-0.0189	-0.0147	-16.4266	0.0003	-12.7833	-39871.2539
0.0110	0.0086	-0.0568	-0.0442	-16.3553	0.0025	-12.7279	-39698.2541
0.0108	0.0084	-0.0941	-0.0732	-16.1365	0.0069	-12.5576	-39167.1510
0.0105	0.0082	-0.1306	-0.1016	-15.7727	0.0133	-12.2745	-38284.0969
0.0101	0.0079	-0.1660	-0.1291	-15.2682	0.0214	-11.8819	-37059.5730
0.0097	0.0075	-0.1998	-0.1555	-14.6291	0.0311	-11.3845	-35508.2172
0.0091	0.0071	-0.2319	-0.1805	-13.8629	0.0419	-10.7883	-33648.5704
0.0085	0.0066	-0.2620	-0.2039	-12.9788	0.0534	-10.1003	-31502.7465
0.0078	0.0061	-0.2897	-0.2254	-11.9873	0.0653	-9.3286	-29096.0323
0.0071	0.0055	-0.3149	-0.2451	-10.8998	0.0772	-8.4823	-26456.4254
0.0063	0.0049	-0.3375	-0.2626	-9.7288	0.0886	-7.5711	-23614.1228
0.0055	0.0043	-0.3571	-0.2779	-8.4874	0.0992	-6.6050	-20600.9725
0.0046	0.0036	-0.3737	-0.2909	-7.1892	0.1087	-5.5947	-17449.9030
0.0038	0.0029	-0.3873	-0.3014	-5.8479	0.1167	-4.5509	-14194.3467
0.0028	0.0022	-0.3976	-0.3095	-4.4774	0.1231	-3.4843	-10867.6730
0.0019	0.0015	-0.4048	-0.3150	-3.0910	0.1275	-2.4055	-7502.6485
0.0009	0.0007	-0.4087	-0.3181	-1.7019	0.1300	-1.3244	-4130.9372
0.0000	0.0000	-0.4095	-0.3187	-0.3224	0.1305	-0.2509	-782.6574
-0.0009	-0.0007	-0.4071	-0.3168	1.0357	0.1290	0.8060	2513.9969
-0.0019	-0.0015	-0.4016	-0.3125	2.3620	0.1255	1.8381	5733.0587
-0.0028	-0.0022	-0.3932	-0.3060	3.6465	0.1203	2.8378	8851.0107
-0.0037	-0.0029	-0.3819	-0.2972	4.8808	0.1135	3.7983	11846.9262
-0.0045	-0.0035	-0.3679	-0.2863	6.0573	0.1053	4.7139	14702.5276
-0.0053	-0.0041	-0.3513	-0.2734	7.1695	0.0960	5.5794	17402.1691
-0.0061	-0.0047	-0.3323	-0.2586	8.2121	0.0859	6.3907	19932.7476
-0.0068	-0.0053	-0.3110	-0.2420	9.1806	0.0753	7.1445	22283.5540
-0.0075	-0.0058	-0.2877	-0.2239	10.0716	0.0644	7.8378	24446.0727
-0.0081	-0.0063	-0.2625	-0.2043	10.8822	0.0536	8.4687	26413.7439
-0.0086	-0.0067	-0.2356	-0.1834	11.6106	0.0432	9.0355	28181.6991
-0.0091	-0.0071	-0.2073	-0.1613	12.2553	0.0334	9.5372	29746.4835
-0.0095	-0.0074	-0.1776	-0.1382	12.8153	0.0245	9.9730	31105.7767
-0.0099	-0.0077	-0.1468	-0.1143	13.2901	0.0168	10.3425	32258.1232
-0.0101	-0.0079	-0.1152	-0.0896	13.6792	0.0103	10.6453	33202.6822
-0.0103	-0.0080	-0.0828	-0.0644	13.9826	0.0053	10.8814	33939.0061
-0.0104	-0.0081	-0.0499	-0.0388	14.2000	0.0019	11.0506	34466.8538
-0.0105	-0.0082	-0.0167	-0.0130	14.3315	0.0002	11.1529	34786.0458

Bending Moment Calculations

Max Positive Moment	34896.4	Nm
Max Negative Moment	-39871.3	Nm
Maximum Moment	39871.3	Nm

Second Moment of Area	1.84E-05	m^4

SHS Dimensions

B, D	0.15	m
H, K	0.13	m

Distance from Neutral Axis (y)

Distance (m)	Stress (Pa)	Stress (MPa)
0.015	3.25E+07	33
0.025	5.42E+07	54
0.035	7.59E+07	76
0.045	9.76E+07	98
0.055	1.19E+08	119
0.065	1.41E+08	141
0.075	1.63E+08	163

Mass / Inertia Calculations

p	7850	kg/m3	Density - Grade 250 Steel

Assumptions

Grade 250 Steel used for all components
Variance in the centroid location for point loads due to material dimensional variances in negligible
Moment caused by boss mass encompassing the pivot pin in negligible
Operation when maximum dust is attached to bag (9kg)
Based on larger fabric filter consisting of 168 bags
Shaker rack is a mass moment acting at the end of the shaker arm

SDCA - Shaker Drive Connection (m_1)

V1	0 00196	m^3	Shaft (Minus 5mm chamfer)
V2	0 00020	m^3	114 diameter section
V3	-0 00012	m^3	Connection Rod penetration
V4	-0 00002	m^3	2 x 45° Chamfer
V5	0 00036	m^3	SHS Internal Plates
V6	0 00017	m^3	SHS End Capping

V	0.0026	m^3	Total Volume

m_1	20.04	kg	Total Mass
r_1	1.0325	m	Acting at central radius from pivot pin

I_1	21.37	$kg.m^2$	Point of mass about pivot pin

SDCA - SHS Above Pivot Pin (m_2)

m/l	43	kg/m	150mm SHS per linear metre
l	0.985	m	SHS Length above pin

m_2	42.36	kg	Mass above pivot pin

I_2	3.42	$kg.m^2$

SDCA - SHS Below Pivot Pin (m_3)

m/l	43	kg/m	150mm SHS per linear metre
l	1.285	m	SHS Length below pin

m_3	55 26	kg	Mass below pivot pin

I_3	7.60	$kg.m^2$

SDCA - Shaker Rack (m_4)

V1	0.00091	m^3	Connection Strap
V2	0.00101	m^3	Crank Block
V3	0.01680	m^3	Shaker Rack - Detailed drawing unavailable
V	0.0187	m^3	

m_{bag}	1	kg	Mass per filter bag
m_{dust}	9	kg	Estimated dust per filter bag pre shake
n_{fb}	168	Qty	Filter bags

m_1	1826.98	kg	
r_1	1.305	m	SHS plus 20mm block extending from base

I_4	3111.40	$kg.m^2$	Point of mass about pivot pin